STRUCTURE

OF

TYPICAL AMERICAN OIL FIELDS

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A SYMPOSIUM ON THE RELATION OF OIL ACCUMULATION TO STRUCTURE

FORTY SPECIAL PAPERS INCLUDING A CRITICAL SUMMARY; IN PART FROM THE PROGRAM OF THE TWELFTH ANNUAL CONVENTION OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS AT TULSA, OKLAHOMA, MARCH 24, 25, AND 26, 1927

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PREFATORY NOTE

The contributions to the *Structure of Typical American Oil Fields* have been solicited from geologists most familiar with the respective fields and have been prepared with a view to showing the relation of petroleum accumulation to structure. In doing this the relation of structure at the surface to that on the oil-bearing horizons has been made clear. The authors have presented their facts, deductions, and theories for individual fields or groups of fields; and, with the assurance that the detailed facts are correct, the reader is free to make generalizations and to apply the conclusions to larger, regional problems.

Attention is invited to the broader aspects of the relation of petroleum accumulation to structure as related (1) to reservoir rocks and (2) to regional sedimentation and tectonics. A comprehensive picture of all the geologic conditions is as necessary to an understanding of petroleum accumulation to-day as was a mere general conception of the structural theory of I. C. White ten years ago, and the importance of comprehensive study will steadily increase.

A few speculations are given in the following paragraphs in order to be suggestive, not dogmatic. The most important of these concern folding contemporaneous with the filling of geosynclinal prisms of accumulation, and refolding along predetermined axes, the location of major lines of folding, especially of other beds in shallow geosynclinal basins, being controlled by lines of weakness in the basement rocks.

The primary control of accumulation in many areas is the physical character of the reservoir rock which determines the type of structural control and the relations of oil, gas, and water. Sandstones, limestones, dolomites, and cherts are the dominant reservoir rocks. A reservoir rock may be widespread with structural accumulation anticlinal where controlled by the presence of water, or synclinal where water is absent. In lenticular porous sandstones, however, accumulation may be determined by the shape of the lens or by hydrostatic equilibrium, or by both; therefore, the oil may occur on monoclinal or homoclinal structure. Limestones and similar rocks act as reservoirs in anticlinal folds and buried hills only where porous, and this porosity is in most areas due to solution at unconformities or to dolomitization. Fracture zones form reservoirs in limestone and shale irrespective of local structure. Under hydraulic head the upthrown side of normal faults, especially the basinward side, may

act as a reservoir for oil, whereas the downthrown side rarely acts as a reservoir except where the faulting took place after accumulation. Readjustment of the oil-water level in faulted anticlinal folds in which accumulation preceded faulting is dependent on the degree of stagnation of the water. Accumulation of oil in overthrust faults is in most places controlled by hydraulic head. Discordant igneous intrusions rarely, if ever, trap oil.

Oil fields are commonly developed in sedimentary rocks deposited in epeiric or mediterranean seas near the edges of geosynclines, but not where the folding or faulting is intense; they occur also within, and even in the centers of, such basins and of major geosynclines. But the apparent total absence of oil from large parts of certain basins, irrespective of proved continuity of reservoir conditions, such as sand lenses, and of continuity of geologic structure from oil fields, is not understood and is a problem of oil genesis or migration, rather than of structure.

Oil and gas seepages have led to initial discovery of many oil fields. After the introduction of geology, visible folds of anticlinal type and, later, similar folds discovered by subsurface studies based on well logs, were drilled with great success. For a decade the drill and seepages, rather than geology, pointed the way to fields in the gently folded rocks in the centers of shallow geosynclines and in smaller intra-continental basins. In recent years a better comprehension of the basic principles of geology as related to petroleum together with intensive scientific exploration has proved the importance of such areas and has already led to the discovery of some of the most important oil fields of the world.

Deductions from studies in the Appalachian Mountains and from the experimental production of folds of Appalachian type have dominated the conception of folding and of mountain-building in the United States. Like the Neptunian doctrines of Abraham Gottlob Werner, these conceptions stood unchallenged for many years. Isostasy and petroleum geology have brought into the science modified views and have shown the true relation of a thin veneer of incompetent sediments to the underlying vast thickness of competent rocks. Structure in the sedimentary rocks, and especially in the thin sheets over many geosynclines, is determined by forces acting in the underlying basement complex. Anticlines, buried hills, faults, and even synclines underground, and especially in or near the basement rocks, may be overlain by entirely different types of structure—by anticlines or salt domes or faults with an entirely different strike or by homoclines. In gently folded rocks the structure underground is more sharply folded and covers less area than at the surface.

Earth movements which initiate epi-continental seas and geosynclines of deposition, and complete geanticlines of compression, act slowly through long periods of time with spasmodic stillstands and slight positive movements which cause disconformities, unconformities, lines of weakness, and incipient lines of folding. In some geosynclines of deposition the loci of the major folds and lines of folding are determined by buried topography or structure or fragmentation in the basement rocks, and superposed folding began during or after the deposition of the lower part of the ultimate sedimentary column, and in the time scale take place several geologic periods before ultimate cessation of sedimentation. These folds are rejuvenated from time to time so that the sedimentary sections in them show initial thinning. Between these primary folds secondary folds and lines of folding are formed later.

Translated into factors of oil accumulation, the time of formation of anticlines and synclines and the time of stillstands and of aerial exposure of newly deposited sediments become very important because at these times the lithological composition and porosity of sedimentary rocks were modified locally. Sand lenses are temporary shallow-water or shore phenomena and may be found far from the original limits of sedimentary basins. Widespread porous limestones may owe their porosity to temporary land conditions and to solution by surface and underground waters before complete lithification of the prism of sediments. Dolomite is evidently a later secondary alteration product of limestone after lithification. Local porosity in limestones may be due to coral or algal reefs which may form interbasin bars of great lineal extent bounded on either side by rocks of different lithological composition.

Anticlines and synclines formed during the last folding of the geosynclinal basin may produce oil. But many of the largest and most prolific oil fields of the world are on primary anticlines of early formation which were refolded once or several times and which show structural discordance not traceable in adjacent synclines. Such primary anticlines form the buried hills and buried ridges which were recognized for the first time thirteen years ago. The older, partly truncated rocks in them may or may not produce oil or may not be within reach of the drill. The upper surface of these older rocks may even be synclinal between buried hills in secondary anticlines yielding oil from younger rocks. Entire anticlinal ridges of secondary folding may be barren although primary anticlines on either side produce oil. There are reasons for believing that one of the pre-

initial thinning in the stratigraphic section; in other words, that the generation and migration of the oil antedated the final folding.

Structure has therefore assumed a new significance in the quest for oil. An anticline in a petroliferous province is not the sole desideratum. Anticlines may be barren and synclines productive. Homoclinal dip may be the proper type of structure. Where accumulation is anticlinal, the history of sedimentation and of folding, as revealed in large extent by subsurface studies, will in many cases differentiate petroliferous and barren anticlines.

Geological thought is evolving rapidly. The contribution of petroleum geology to knowledge of structure, stratigraphy, and paleontology is becoming ever more important. Research now accompanies and follows observation. Comprehension of the nature and origin of folding has been hampered by lack of knowledge of the third dimension. Well data are supplying this information. *Structure of Typical American Oil Fields* is, therefore, a contribution to research. May it stimulate a better understanding of structural geology as well as aid in the discovery of new oil fields the world over.

SIDNEY POWERS

TULSA, OKLAHOMA
March 6, 1929

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W. C. SPOONER[2]
Shreveport, Louisiana

ABSTRACT

The Stephens field, discovered in 1922, has produced 3,137,448 barrels of oil to January 1, 1928. The estimated future production is 2,175,000 barrels. It is estimated that the ultimate average acre-yield will be 1,875 barrels. The production is mainly from the Buckrange sand, the basal member of the Ozan formation, but a small volume of oil and gas is obtained from the Nacatoch sand. Both producing horizons are in the Upper Cretaceous. The structure of the field is a southeastward-trending structural nose, limited on the north by a graben. The lenticular structure of the reservoir sand has determined the distribution of the oil.

LOCATION AND EXTENT

The Stephens field is in T. 15 S., R. 20 W., Columbia County, and T. 15 S., R. 19 W., Ouachita County, Arkansas. Most of the wells were drilled in Columbia County. The field is named from the town of Stephens in Sec. 21, T. 15 S., R. 19 W., Ouachita County.

The nearest producing areas are the Louann district of the Smackover field, 12 miles east; and the Irma field, the same distance northwest of Stephens.

The total area of the Stephens field capable of producing oil is not easily determinable because the small initial yield of the wells has not been encouraging to complete drilling of the leases. The total producing area has been arbitrarily fixed at 2,850 acres, based upon the ratio of one well to each 10 acres.

HISTORY OF DEVELOPMENT

The discovery well of the Stephens field, Hude and Aarnes' Brown No. 1, in Sec. 13, T. 15 S., R. 20 W., Columbia County, was completed on June 8, 1922, at a total depth of 2,082 feet. The initial production was 33 barrels of 29.3° Bé. oil from the Buckrange sand, recorded from 2,078 to 2,082 feet in depth.

[1] Manuscript received by the editor, November 16, 1928. Published by the permission of the Arkansas Geological Survey, for which Mr. Spooner was acting as assistant geologist when he wrote this paper.

[2] Consulting geologist, Ardis Building.

The first well drilled in the Stephens area was the S. S. Hunter *et al.*, Lester and Haltom No. 1 in Sec. 13, T. 15 S., R. 19 W., Ouachita County, completed on July 16, 1920. It produced a small amount of oil from a depth of 2,125–2,131 feet. Subsequent development proved this well to be located on the downthrown side of the fault, which limits the producing area on the north side of the field. The showing of oil in this well stimulated the search for oil in Arkansas, which led to the discovery of the Stephens, El Dorado, and Smackover fields.

In 1922 the Stephens field produced 28,325 barrels of oil. The greatest production was in 1924, with a total of 787,133 barrels. The highest monthly production was recorded in August, 1923, with a total of 88,899 barrels as compared with a total of 35,930 barrels for the month of August, 1928.

TOPOGRAPHY

The Stephens field is drained by the eastward-flowing Smackover Creek. It has a broad, flat valley with an average altitude of 190 feet above sea-level. The interstream areas are gently rolling hill-lands that range in altitude from 240 to 290 feet above sea-level. The higher altitudes are in the western part of the field.

STRATIGRAPHY

Surface formations in the Stephens field belong to the Claiborne group of the Eocene. They consist of massive light-colored and reddish sand and thin-bedded ferruginous clay and sand, in part indurated and containing some limonite and glauconite. Deep wells in the field have penetrated all of the Gulf series and more than 1,000 feet of the Trinity group of the Comanche series, and wells a short distance away from the field have penetrated an even greater thickness of the Trinity group. The geologic column for the field is given in Table I.

COMANCHE SERIES (LOWER CRETACEOUS)

The Comanche series is represented in the Stephens field by the equivalents of the Glen Rose limestone and by the Red shale and sand zone of the Trinity group (Fig. 1). The total thickness of the Comanche rocks in the area, estimated from wells adjacent to the field, is more than 2,500 feet. The Washita and Fredericksburg groups, as well as the upper part of the Trinity group, were removed by erosion prior to the deposition of the Gulf series.

Red shale and sand zone.—The basal beds of the Trinity group are in this area represented by 1,500–2,000 feet of beds herein designated as

TABLE I

GENERALIZED SECTION OF FORMATIONS IN THE STEPHENS FIELD

System	Series	Group	Formation	Thickness in Feet	Character
Tertiary	Eocene	Claiborne	Undifferentiated	300–400	Sand, sandy clay, and ferruginous sand and clay. Some glauconitic sand at the base
		Wilcox	Wilcox	550	Light-colored to brown sand, sandy clay, and clay. In part lignitic. Non-marine
		Midway	Midway clay	500	Gray non-calcareous clay and shale. Lower 50 feet gray and dark blue shale with fossils
			Unconformity		
Cretaceous	Gulf series	Navarro	Arkadelphia clay	90–100	Dark gray to black shale, in part chalky
			Nacatoch sand	315	Sand and sandy shale, calcareous sandstone, and sandy limestone, lower 100 feet gray shale
			Saratoga chalk	15–30	Gray and white chalk
		Taylor	Marlbrook marl	225	Gray marl and shale, in part chalky
			Annona chalk	30–50	White and bluish-gray chalk
			Ozan (Buckrange sand at the base)	110	Gray shale and fine, sandy shale. Buckrange sand 30 to 50 feet at the base
			Brownstown marl		Medium to dark gray shale and fine-textured sandy shale and sand
		Austin	Tokio formation	450	Gray shale, sandy shale, and sand, some glauconite and volcanic ash
			Woodbine sand		Arkosic sand with matrix of volcanic ash
			Unconformity		
	Comanche series	Washita	Absent		
		Fredericksburg	Absent		

TABLE I—*Continued*

System	Series	Group	Formation	Thickness in Feet	Character
Cretaceous	Comanche series	Trinity	Glen Rose limestone (DeQueen limestone) (Dierks limestone)	1,000–1,100	Gray and greenish-gray shale, some red and brown shale, argillaceous limestone and sand
			Red sand and shale zone	1,500+	Red shale and sand, light-colored sand of fine texture. Not penetrated in the field, but recorded in deep well a short distance away

the "Red shale and sand" zone of the Trinity group. Because of a northward overlap, these beds are not present at the outcrop in southwestern Arkansas. Only a few hundred feet of the zone has been penetrated in wells drilled in the Stephens field; but a well a few miles toward the northwest penetrated 1,000 feet, and wells in the Smackover field have penetrated more than 1,700 feet of these beds. The total thickness of this zone is estimated to be nearly 2,000 feet.

The "Red shale and sand" zone is made up of fine-textured sand and sandstone, fine-textured sandy clay, and shale. The shale is commonly red, and this is particularly true of the upper beds ranging in thickness from 800 to 1,000 feet. The sand and sandstone are in part lignitic and in part slightly calcareous. Sand makes up the larger part of the zone.

Glen Rose formation.—The Glen Rose formation is represented by beds that in part are the equivalent of the DeQueen limestone, the Holly Creek shale and sand, and the Dierks limestone of southwestern Arkansas. The formation ranges from 1,000 to 1,100 feet in thickness. The lower part of the section is probably older than the Dierks limestone.

The upper 400 feet of the Glen Rose formation is made up chiefly of gray, greenish-gray, and red shale and sandy shale with subordinate beds of limestone and sandstone. The lower beds, ranging from 600 to 700 feet in thickness, are made up of limestone; greenish-gray, gray, and blue shale; sandy shale; and sandstone; with a few thin beds of brown and reddish-brown shale. The sand is uniformly fine-textured throughout the section, and the limestone is in part oölitic. Macro-fossils and micro-fossils are not plentiful except in a few thin beds of limestone and shale.

EVENTS PRECEDING DEPOSITION OF GULF SERIES

At the close of the Comanche epoch the sediments were uplifted and tilted westward. The uplift was followed by a period of erosion during

which the beds were truncated and the terrane reduced to a peneplain. In the Stephens field the Washita and Fredericksburg groups are absent, as is most of the upper Trinity, which in the western part of the state has a thickness of several hundred feet. In the Smackover field, 15 miles toward the east, the Glen Rose formation is absent and the basal Upper Cretaceous is in contact with the "Red shale and sand" zone of the Trinity group.

GULF SERIES (UPPER CRETACEOUS)

The Gulf series underlying the Stephens field (Fig. 2) has a thickness of 1,250 feet representing nine formations, of which a summary description follows.

Woodbine sand.—The Woodbine sand is not readily differentiated from the overlying beds of the Tokio formation. Both formations contain volcanic material, and the conglomerate bed which at the outcrop marks the base of the Tokio formation is absent in the Stephens field. The lower beds, ranging in thickness from 50 to 100 feet, are somewhat more arkosic and contain a greater proportion of volcanic material, on which basis they are assigned to the Woodbine sand rather than to the Tokio formation.

Tokio formation and Brownstown marl.—The Tokio formation of the Austin group and the Brownstown marl of the Taylor group are not easily differentiated. They have a combined thickness ranging from 400 to 450 feet. The Tokio formation is distinctly sandy, in part lignitic, and contains some volcanic material, ordinarily in the form of bentonite. The clays are gray and pale greenish-gray and contain considerable amounts of very fine-textured sand. The sand members make up the greater part of the formation. The Brownstown marl is composed mainly

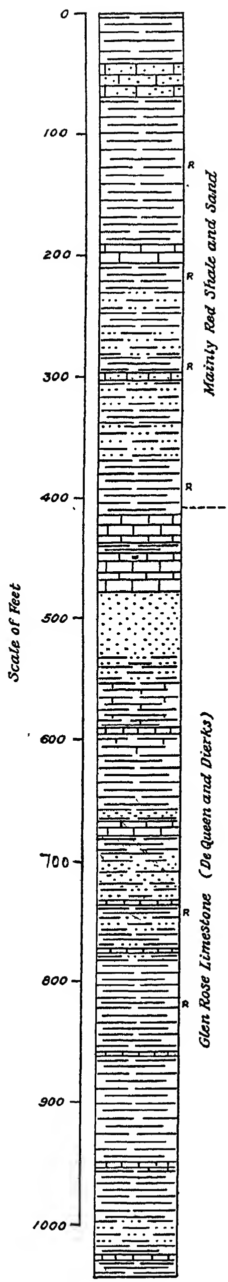

FIG. 1.—Section of Comanche rocks penetrated in Hude and Aarnes' Brown No. 2 well in Sec. 13, T. 15 S., R. 20 W.

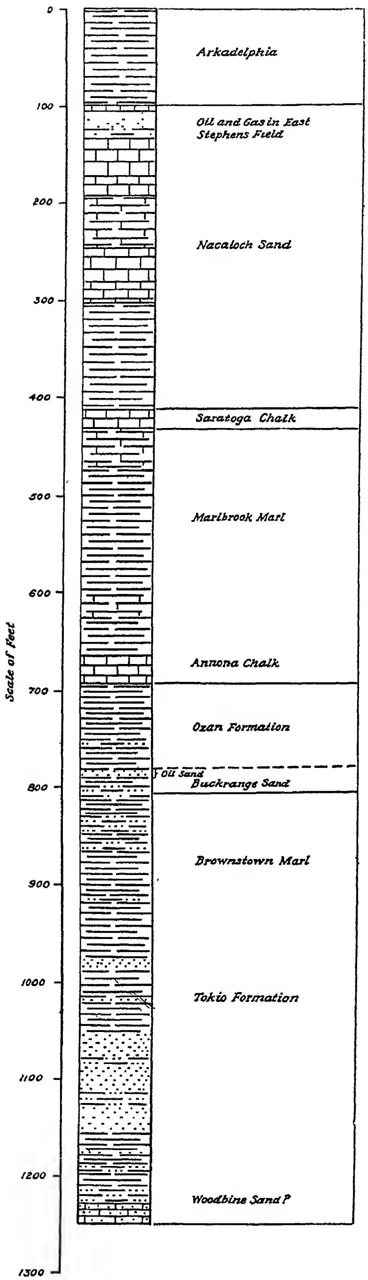

FIG. 2.—Section of Gulf series in the Stephens field.

of gray shale and sandy shale. The sand, as in the Tokio formation, is fine-textured.

Ozan formation.—The Ozan formation is made up of gray shale containing a slight amount of fine-textured sand. Its thickness ranges from 80 to 100 feet. The lower part of the formation, ranging from 15 to 30 feet in thickness, is the Buckrange sand member ("Blossom" sand), the main oil-producing horizon of the Stephens field.

Annona chalk.—The Annona chalk as a litholigic unit has a thickness ranging from 30 to 50 feet. It consists of hard white and gray chalk. Some of the chalky clay overlying the chalk may belong in the Annona, but, lacking more definite evidence, it is included in the Marlbrook marl.

Marlbrook marl.—To the Marlbrook marl is assigned 225 feet of light-colored clay and marl, in part chalky, overlying the Annona chalk.

Saratoga chalk.—This formation consists of hard white and gray chalk ranging from 15 to 30 feet in thickness.

Nacatoch sand.—This formation is made up of three more or less well defined members. The upper 10–35 feet is sandy shale containing thin lenses and beds of sand. The middle member, whose thickness ranges from 150 to 175 feet, is made up chiefly of calcareous sandstone with subordinate beds of limestone. The basal member, 100 feet in thick-

ness, consists of gray and blue shale. The total thickness of the Nacatoch sand is 315 feet.

Arkadelphia clay.—The Arkadelphia has a thickness ranging from 90 to 100 feet. It is composed of dark gray clay and shale.

EOCENE (LOWER TERTIARY)

Midway clay.—The Midway formation has a thickness ranging from 500 to 550 feet. It consists of gray clay and shale containing many siderite concretions. With the exception of the lower fossiliferous beds, ranging from 50 to 100 feet in thickness, the Midway clay is non-calcareous.

Wilcox formation.—This formation has a thickness ranging from 550 to 600 feet. It is made up mainly of sands and sandy clays and is in part lignitic. Where wells have been carefully cored, it is possible to divide the Wilcox formation into four parts. At the base is 100–150 feet of sandy clay, ordinarily with a thin bed of lignite or lignitic clay at the base. These beds are overlain by 300–325 feet of massive red sand. Above the massive sand is 75 feet of gray clay characterized by many siderite concretions. At the top is 100 feet of gray sand, in part lignitic.

Claiborne group.—The Claiborne group in the Stephens field is composed of massive sand with subordinate beds of clay containing concretions of limonite and siderite. Its thickness ranges from 300 to 400 feet. Because of the absence of fossils which are present in the Claiborne in Louisiana and Texas as well as in southwestern Arkansas, it is not possible definitely to divide the group into formations, as has been done where marine beds are present.

PRODUCING HORIZONS

The principal producing horizon of the Stephens field is the Buckrange sand member at the base of the Ozan formation. This sand is also called the "Stephens" sand and the "Blossom" sand. The Nacatoch sand has yielded a few small oil and gas wells in the area east of the town of Stephens, but it is not an important producing horizon.

Buckrange sand.—This sand is the basal member of the Ozan formation as defined by C. H. Dane.[1] It is correlated with the Graves sand of the Smackover field and with the producing sand of the Haynesville field, generally called the "Blossom" sand.

The Buckrange sand in the Stephens field has a thickness ranging from 30 to 50 feet consisting of sand and sandy shale. Oil is produced

[1] C. H. Dane, "Oil-bearing Formations of Southwestern Arkansas," *U. S. Geol. Survey Press Bull.*, September 10, 1926.

from the upper 5–10 feet of sand. The remainder of the section consists of sandy shale with intercalated thin lenses of sand.

The sand is made up of fine-textured, generally sub-rounded quartz grains with some grains of glauconite and fine particles of mica. The porosity is uniformily low, but variable depending upon the amount of secondary cementation and the amount of argillaceous matter it contains as a matrix.

The most uniform porosity is in the main part of the field, whence it decreases in all directions. The sand becomes thinner within a short distance toward the west and almost disappears on the west side of the field, thus limiting production in that direction. The Buckrange sand ranges in depth from 1,890 to 1,960 feet below sea-level.

Nacatoch sand.—The Nacatoch sand has yielded showings of oil and gas in the main part of the field, but no production. In the east field there are a few wells producing gas and heavy oil from the top of the Nacatoch sand, but the production is of little importance. Oil is produced from the uppermost 15 feet of the Nacatoch sand, which consists of thin beds of alternating sand and shale. The Nacatoch is found at depths ranging from 1,150 to 1,300 feet below sea-level.

SURFACE STRUCTURE

The structure of the Stephens field is not easily determined from an examination of the surface because of the slight structural relief and the character of the beds that crop out in the area. The fault on the north can, however, be traced throughout a considerable part of its length.

SUBSURFACE STRUCTURE

The generalized structure of the Stephens field and the adjacent area is shown in Figure 3. The contours are drawn on top of the Nacatoch sand and show depths below sea-level. According to the writer's interpretation, the structure is that of a terrace or nose that is limited on the north by a graben. The regional dip is toward the south and the southeast. The faults that define the graben have a general northwest trend, and the width of the graben is about 2 miles. The maximum throw is 250 feet, but it decreases to a few feet in the northwestern corner of the area shown in Figure 3. At the southeast the data are inadequate to form an estimate of the amount of throw. The dip of the fault plane is not easily determined because of lack of accurate data, but it is probably not less than 70° from the horizontal.

The structure of the main producing area is shown in detail in Figure 4. The contours are drawn on top of the Buckrange sand, and figures show depths below sea-level. Mapped in detail, the structure is seen to be a low-dipping, southeast-plunging nose. Along the axis the dips range from 15 to 25 feet per mile, but they increase toward the south and the north, ranging from 50 to 75 feet per mile.

The structure of what is commonly called the "east Stephens field" is shown in Figure 5. The contours are drawn on top of the Nacatoch

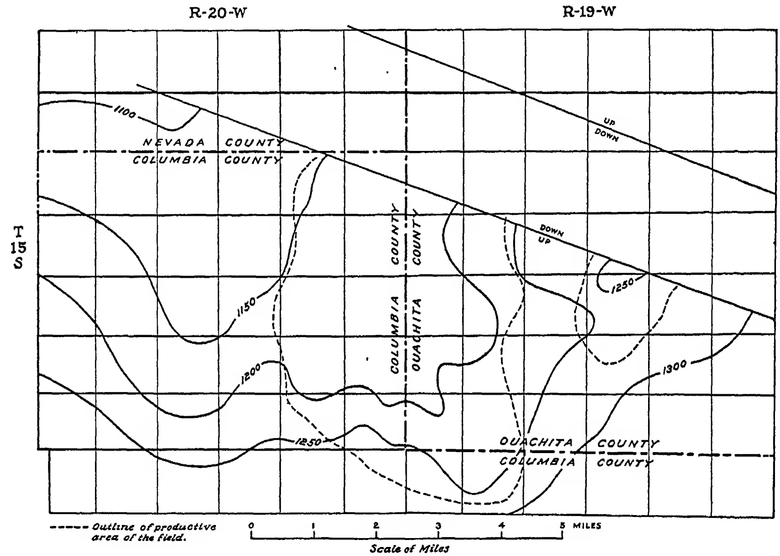

FIG. 3.—Generalized subsurface structure of the Stephens field and adjacent area. Contours drawn on top of Nacatoch sand. Figures give depths below sea-level.

sand at intervals of 10 feet. By using the smaller contour interval, it is possible to show a contour closing against the fault.

The structure of the Trinity rocks may, because of the unconformity that separates them from the Gulf series, differ greatly from the structure mapped on the younger rocks. But, owing to lack of data, it is impossible even to speculate upon the local structural features in the Trinity group.

RELATION OF STRUCTURE TO ACCUMULATION OF OIL

The Stephens field and the adjacent area on the west is a structural "high," which may have been the factor that determined the accumulation in this area. This distribution of the oil, however, was determined

by the character of the reservoir sand, chiefly its lenticular structure. The distribution has also been modified by differences in the completeness of secondary cementation and the amount of argillaceous material contained in the sand.

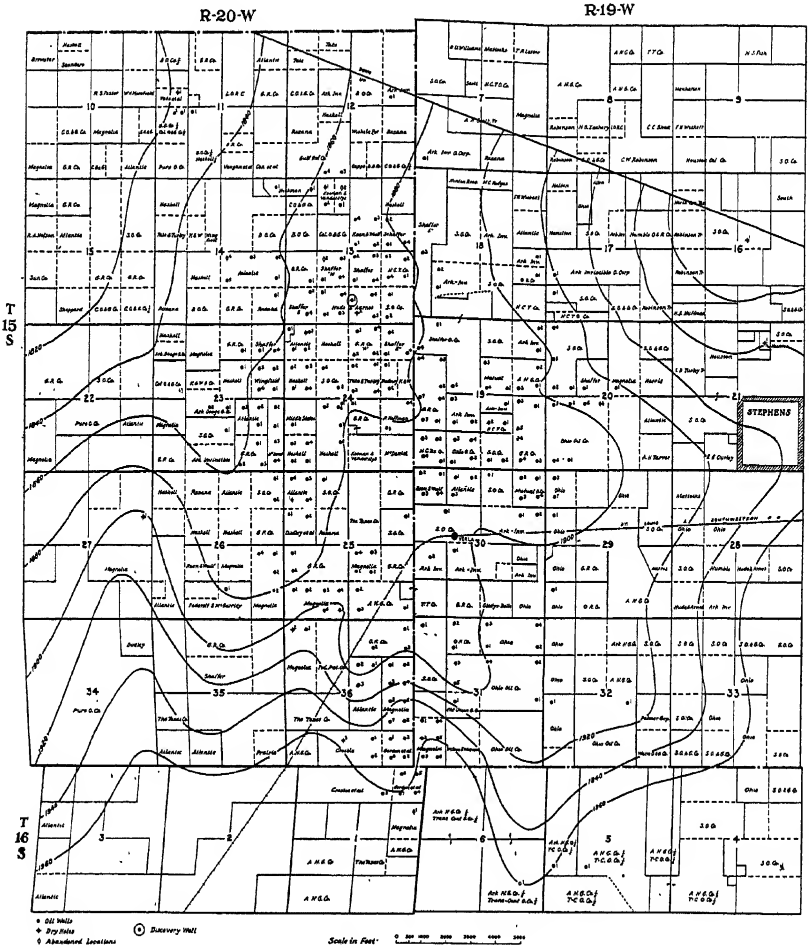

FIG. 4.—Detailed subsurface structure map of Stephens field. Contours drawn on top of Buckrange (producing) sand. Figures give depths below sea-level.

AGE OF THE DEFORMATION

Two principal periods of deformation are recognized in the area. The earlier was at the close of the Comanche epoch. The nature of the

deformation of this period is not known in the Stephens field for lack of data.

The later period was post-Claiborne; and, so far as can be deduced from the physiographic history, it dates from the Miocene epoch.

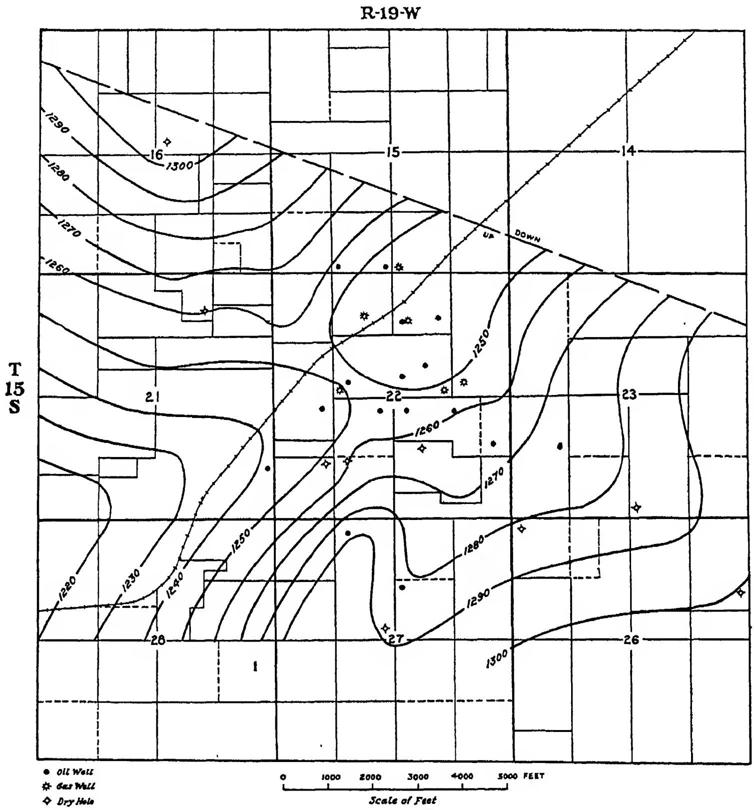

FIG. 5.—Subsurface structure of east Stephens field. Contours drawn on top of Nacatoch sand. Figures give depths below sea-level.

POSSIBILITIES OF DEEPER PRODUCING HORIZONS

The Tokio formation and the Woodbine sand contain excellent reservoir sands, which have been penetrated only in a few wells, yielding slight showings of oil. These sands are conformable with the Buckrange sand but more uniform in porosity and thickness, and would, therefore, be more dependent upon local anticlinal structure. As the distribution of

the oil in the Buckrange sand is controlled primarily by the lenticular structure of the sand, it necessarily follows that any oil that may be present in the lower, more uniform sands might have a totally different areal distribution. The data are inadequate to form an estimate of their potentiality.

The Trinity group contains several sands capable of serving as reservoirs for oil and gas, one of which yielded an excellent showing of oil in Hude and Aarnes' Brown No. 2 well in Sec. 13, T. 15 S., R. 20 W. The Comanche sediments were uplifted, tilted, and perhaps folded locally, and subjected to erosion prior to the deposition of the Gulf series. The resultant unconformity was of such magnitude that the available information gives no indication of the structure in this area.

DRILLING METHODS

The rotary method of drilling was used exclusively in the Stephens field. Neither drilling nor the completion of the wells presented any difficulties worthy of note.

The common practice was to set 100–150 feet of 10-inch casing to exclude the surface waters. The wells completed in the Buckrange sand were set with 1,975–2,025 feet of 6-inch casing and completed with 70–90 feet of $4\frac{1}{2}$-inch blank, and 35–45 feet of $4\frac{1}{2}$-inch perforated, liner. The wells completed in the Nacatoch sand were set with 1,450–1,510 feet of 6-inch casing and completed with 40–100 feet of $4\frac{1}{2}$-inch liner.

PRODUCING AREA

The total area capable of producing oil in some quantity is not easily determined because the small initial volume of the wells was not sufficient inducement to drill the field according to a definite schedule of well spacing. Where leases were completely drilled, the wells were spaced on the basis of 10 acres per well. In order to arrive at a representative acre-yield for the field, it has been assumed that the producing area includes 10 acres for each well drilled, this assumption giving a total of 2,850 acres.

INITIAL AND PRESENT PRODUCTION OF WELLS

The initial production of the wells in the Stephens field was low compared with that of other fields in Arkansas. The Buckrange sand yielded wells with initial production varying from 75 to 100 barrels per day, but the average was about 25 barrels per day. The Nacatoch sand wells had higher initial production, ranging from 50 to 400 barrels per day. The gas wells had initial yields from 3,000,000 to 15,000,000 cubic feet per day.

TABLE II

PROPERTIES OF CRUDE OIL

SAMPLE NO. 281001, MARK A: ARKANSAS, STEPHENS FIELD, OUACHITA COUNTY, BUCKRANGE SAND, SEC. 21, T. 15 S., R. 19 W., WELL NO. 2

Specific gravity................0.877	Saybolt Universal viscosity at 100° F. ....81 sec.
A.P.I. gravity..................29.9°	Percentage of water..............0.7
Percentage of sulphur............1.63	Pour point................below 5° F.
Saybolt Universal viscosity at 70° F. ....130 sec.	Color.............. ...brownish black

DISTILLATION: BUREAU OF MINES, HEMPEL METHOD

Temperature	Percentage Cut	Sum, Percentage	Specific Gravity of Cut	A.P.I. of Cut	Viscosity at 100° F.	Cloud Test (Degrees F.)	Temperature (Degrees F.)
Air Distillation. Barometer, 744 Mm. First Drop, 49° C. (120° F.)							
Up to 50	......	......	......	......	......	......	Up to 122
50–75	4.7	4.7	0.683	75.7	......	......	122–67
75–100	3.9	8.6	0.707	68.6	......	......	167–212
100–125	1.1	9.7	......	......	......	......	212–57
125–50	3.5	13.2	0.736	60.8	......	......	257–302
150–75	4.0	17.2	0.758	55.2	......	......	302–47
175–200	4.2	21.4	0.778	50.4	......	......	347–92
200–225	4.4	25.8	0.795	46.5	......	......	392–437
225–50	4.6	30.4	0.810	43.2	......	......	437–82
250–75	5.8	36.2	0.826	39.8	......	......	482–527
Vacuum Distillation at 40 Mm.							
Up to 200	4.1	4.1	0.851	34.8	41	10	Up to 392
200–225	5.3	9.4	0.858	33.4	45	25	392–437
225–50	5.6	15.0	0.874	30.4	57	45	437–82
250–75	5.8	20.8	0.890	27.5	80	65	482–527
275–300	5.7	26.5	0.901	25.6	130	80	527–72

Residuum, per cent...............36.9	Distillation loss, per cent...........0.4
Carbon residue of residuum, per cent 15.1	Carbon residue of crude, per cent.....5.6

APPROXIMATE SUMMARY

	Percentage	Specific Gravity	A.P.I.	Viscosity
Light gasoline (end-point, 212° F.)	8.6	0.694	72.4	....
Total gasoline and naphtha	21.4	0.731	62.1	....
Kerosene distillate	9.0	0.803	44.7	....
Gas oil	15.0	0.844	36.2	....
Non-viscous lubricating distillate	11.0	0.865–0.894	32.1–26.8	50–100
Medium lubricating distillate	6.3	0.894–0.906	26.8–24.7	100–200
Viscous lubricating distillate	0.0	....	....	Above 200
Residuum	36.9	0.985	12.2	....
Distillation loss	0.4	....	....	....

D. B. Taliaferro, Jr., September 22, 1928

TABLE II—*Continued*

SAMPLE NO. 281002, MARK B: ARKANSAS, STEPHENS FIELD, OUACHITA COUNTY, NACATOCH SAND, SEC. 21, T 15 S., R. 19 W., WELL NO. 1

Specific gravity..................0.982
A.P.I. gravity....................12.6°
Percentage of sulphur............2.87
Saybolt Universal viscosity at 70° F. ....sec.
Saybolt Universal viscosity at 100° F ....above 2,000 sec.
Percentage of water..............29.2
Pour point.......................25° F.
Color.................brownish black

DISTILLATION: BUREAU OF MINES—HEMPEL METHODS

Temperature	Percentage Cut	Sum Percentage	Specific Gravity of Cut	A.P.I. of Cut	Viscosity at 100° F.	Cloud Test (Degrees F.)	Temperature (Degrees F.)
Air Distillation. Barometer, 745 Mm. First Drop, 230° C. (446° F.)							
Up to 50	......	......	......	......	......	......	Up to 122
50–75	......	......	......	......	......	......	122–67
75–100	......	......	......	......	......	......	167–212
100–125	......	......	......	......	......	......	212–57
125–50	......	......	......	......	......	......	257–302
150–75	......	......	......	......	......	......	302–47
175–200	......	......	......	......	......	......	347–92
200–225	......	......	......	......	......	......	392–437
225–50	2.0	2.0:	......	......	......	......	437–82
250–75	5.4	7.4:	0.860	33.0			482–527
Vacuum Distillation at 40 Mm.							
Up to 200	1.9	1.9	0.889	27.7	45	Too dark to obtain cloud	Up to 392
200–225	6.5	8.4	0.895	26.6	54		392–437
225–50	6.4	14.8	0.913	23.5	75		437–82
250–75	7.7	22.5	0.929	20.8	135		482–527
275–300	6.1	28.6	0.942	18.7	260		527–72

Residuum, per cent...............63.1
Carbon residue of residuum, per cent 16.5
Distillation loss, per cent...........0.9
Carbon residue of crude, per cent... 10.4

APPROXIMATE SUMMARY

	Percentage	Specific Gravity	A.P.I.	Viscosity
Light gasoline (end-point, 212° F.)	0.0	....	....	
Total gasoline and naphtha	0.0	....	....	
Kerosene distillate	0.0	....	....	
Gas oil	10.8	0.869	31.3	
Non-viscous lubricating distillate	11.1	0.892–0.920	27.1–22.3	50–100
Medium lubricating distillate	7.7	0.920–0.936	22.3–19.7	100–200
Viscous lubricating distillate	6.4	0.936–0.947	19.7–17.9	Above 200
Residuum	63.1	1.006	....	
Distillation loss	0.9	....	....	

D. B. Taliaferro, Jr., September 22, 1928

Altogether, 289 wells were completed: 283 oil, and 6 gas, wells. During the month of August, 1928, 260 wells in the Buckrange sand produced 979 barrels, an average of 4 barrels per well. Four wells in the Nacatoch sand produced 65 barrels per day, or an average of 16 barrels per well. The average daily production for the month was 1,044 barrels.

WATER CONDITIONS

The Nacatoch sand is water-bearing, and all of the wells in this formation make a considerable amount of water. The Buckrange sand, on the contrary, does not carry water. In the few wells that make water the trouble can be traced to faulty casing seat or bad casing.

PRODUCTION STATISTICS

The Stephens field to January 1, 1928, had produced 3,137,448 barrels of oil, distributed as shown in Table III.

TABLE III

PRODUCTION OF OIL, STEPHENS FIELD

Year	Barrels
1922	28,325
1923	625,218
1924	787,133
1925	642,967
1926	552,131
1927	501,674
Total	3,137,448

The average daily production for August, 1928, was 1,044 barrels from 264 wells, an average of 4 barrels per well. On the basis of 2,850 acres in the producing area, the field had an acre-yield on January 1, 1928, of 1,100 barrels.

ESTIMATED FUTURE PRODUCTION

A production decline curve of the Stephens field is given in Figure 6, which has been used in estimating the future production throughout a period of eight years, giving the result shown in Table IV.

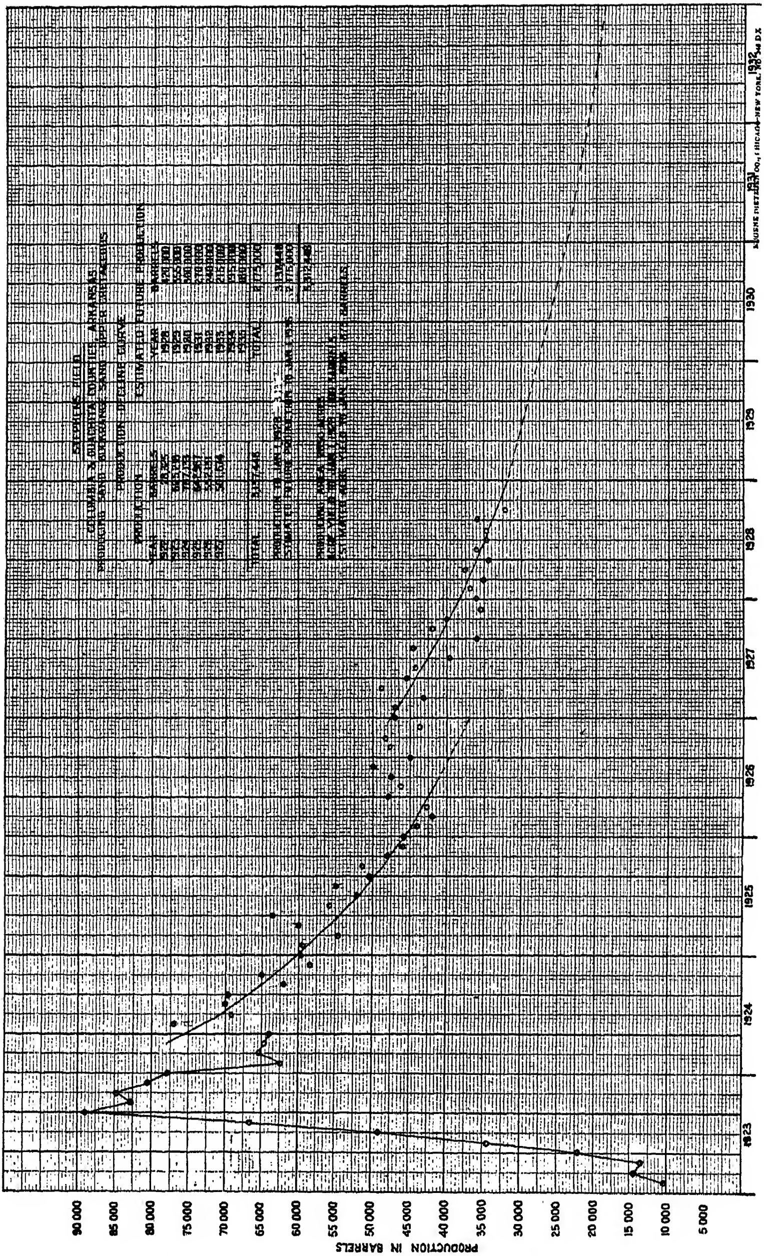

FIG. 6.—Production decline curve for Stephens field.

TABLE IV

ESTIMATED FUTURE PRODUCTION, STEPHENS FIELD

Year	Barrels
1928	420,000
1929	355,000
1930	300,000
1931	270,000
1932	240,000
1933	215,000
1934	195,000
1935	180,000
Total	2,175,000

SUMMARY OF PRODUCTION

The total production to January 1, 1928, was 3,137,448 barrels, and the estimated future production is 2,175,000, giving a total ultimate yield of 5,312,000 barrels. On the basis of 2,850 acres as the total producing area, these figures represent an acre-yield of 1,875 barrels.

OIL ACCUMULATION AND STRUCTURE OF THE SANTA MARIA DISTRICT, SANTA BARBARA COUNTY, CALIFORNIA[1]

R. E. COLLOM[2]
Los Angeles, California

ABSTRACT

In the four oil fields of the Santa Maria district, namely, Casmalia, Cat Canyon, Lompoc, and Santa Maria, the reservoirs have been formed in the rocks where the oil and gas originated. The oil occurs in cross-faulted anticlines in which the faults have influenced the movement and location of the oil. In the Santa Maria district the oil comes from the diatomaceous Monterey shale of Miocene age. Although the diatomaceous shales have been commonly considered the source of the oil and gas, more recent studies have indicated that these highly organic sediments may have been deposited under conditions that would preclude their contribution of any hydrocarbons.

Four producing oil fields are included in the Santa Maria district, which lies in the northwestern part of Santa Barbara County, California; they are Casmalia, Cat Canyon, Lompoc, and Santa Maria (Fig. 1). These fields offer a good opportunity for study of the perplexing problems of the origin, migration, and accumulation of those California crudes which are supposed to have had their source in the widespread organic shales of the Miocene, commonly called the Monterey.

Here is a district in which the existing reservoirs of oil and gas have formed within the mother-rocks.

In the Santa Maria field, which structurally is a cross-faulted anticline, oil occurs in, and is produced from, the fractured, flinty shales of the lower Monterey, the shales in which it probably originated. Similar conditions of occurrence and production of oil are found at Casmalia and Lompoc. In a part of the Santa Maria field, oil also is produced from sand strata of the Vaqueros, which underlies the Monterey. Probably this Vaqueros oil migrated laterally across a fault from the Monterey, where the Vaqueros beds on one side of the fault were upwardly brought into contact with the lower Monterey on the other side.

In the Casmalia field, production comes from the approximate stratigraphic equivalent of the second oil zone—flinty shales—of the Santa

[1] Manuscript received by the editor, October 15, 1928.

[2] Vice-president, Marland Oil Company of California.

FIG. 1.—Oil fields of Santa Maria district, California. Length of area mapped, approximately 54 miles. Topographic contour interval, 25 feet. Map from U. S. Geological Survey.

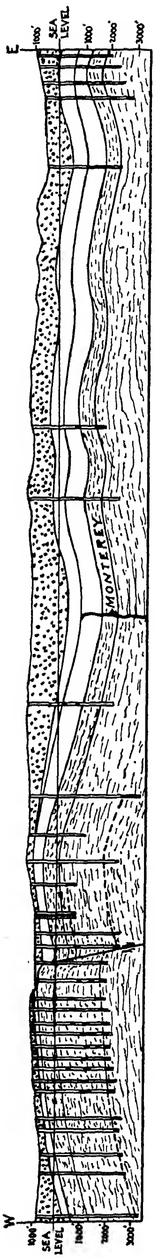

FIG. 2.—West-east cross section through Santa Maria and Cat Canyon oil fields. Depths in feet.

Maria field. There is a marked difference in the gravities of the oil. The Santa Maria crude is the lightest in the district, probably because the closed structure inhibits the dissipation of the lighter fractions. As one progresses westerly along the Schuman anticline, within which the block-faulted accumulation at Casmalia is contained, the entire Miocene series is exposed in outcrop. This condition has evidently permitted the dissipation of lighter fractions of the crude. Hot salt water is closely associated with the oil in this structure, the temperature at depths ranging from 1,500 to 1,800 feet being as high as 145° F. Were it not for this heat, it is doubtful if the heavy, viscous crude could have been successfully produced.

At Cat Canyon the oil occurs in sand strata. According to some geologists, this condition is an inshore phase of sedimentation in shales overlying the productive horizons in the Santa Maria field (Fig. 2). Cores taken from deep tests at Cat Canyon, which have indicated steep-dipping beds of the hard flinty Monterey shales, suggest a possible unconformity between the Monterey and the overlying sand and shale strata containing the oil. Possibly the Cat Canyon production occurs in rocks which are not Monterey but the equivalent of the Santa Margarita of the Huasna district on the north, lying unconformably upon the Monterey and underlying the Fernando.

Ample evidence of faulting and shearing is presented in the Monterey shales of the Santa Maria district, particularly in those areas not masked by younger sediments. A study of this evidence enables the geologist to infer what may have been the structural reactions and final attitude of these mother-shales in the Pliocene oil fields on the south in Ventura County and the Los Angeles basin. It seems probable that post-Pliocene movements along old major lines of faulting in the Monterey not only produced anticlinal folds in the Pliocene blanket

but created favorable channels for escape of oil from the Monterey into overlying sand reservoirs of the Pliocene. The evidence, particularly of the Casmalia and Santa Maria fields, is that the Monterey shales were not capable of extended simple structural adjustments but yielded greatly to differential shearing and faulting.

The producing fields of the Santa Maria district, and any other possible reservoirs of oil that are as yet undiscovered, represent only a small part of the original petroliferous product of these organic shales. Seepages and residues of petroleum may be seen in the broken and unsealed Monterey shales all along the coastal area wherever they are exposed, from Monterey to Santa Barbara. In numerous outcrops of the lower Monterey of the Santa Maria district the innumerable small fractures and crevices in the shales are filled with tar. Heavy oil, in some places, seeps from the shales. In Foxen Canyon is an old inclined pit, sunk on a stratum of steep-tilted shale, the fractures of which are filled with gilsonite. Wherever the older strata of Monterey are exposed in Santa Barbara County, whether in the San Rafael Mountains or along the coast near Santa Barbara, tar fills the fractures, or heavy oil exudes along some fracture plane. On the crest of the hills near the Casmalia field is a great mass of so-called "oil shale." Actually this material is a porous, diatomaceous shale saturated with crude oil. This area has been the scene of several experimental plants built to extract oil from these shales.

To the scientist who is not satisfied with this residual evidence but desires to search further for basic evidence as to the organic origin of Monterey oil, the shales of the Santa Maria district give a far from monotonous array of organic material. At one time the words "Diatomaceous shales" and "Monterey shales" were used almost synonymously in discussions of these Miocene rocks. Recent studies have shown, however, that the organic content of these shale strata is quite different in different places. In some places *Foraminifera* abound; in others, vast quantities of the shale seem to be composed almost entirely of skeletons of diatoms; and in still others, the material may be largely sponge spicules. These various conditions are interestingly reported by Tolman[1] in a summary of field and microscopic studies of the Tertiary organic siliceous sediments of California.

These recent studies show that the old idea that the "Diatomaceous shales" of California were uniformly the generator rocks of petroleum cannot be so simply applied. Great masses of white, porous diatomite,

[1] C. F. Tolman, "Biogenesis of Hydrocarbons by Diatoms," *Econ. Geol.*, Vol. 22, No. 5 (August, 1927), pp. 454–74.

made up mostly of diatom skeletal débris, seem to have been deposited under conditions which would preclude their having contributed any hydrocarbons whatever to existing supply. On the other hand, examination of the opal or "flinty" shales indicates that, under certain conditions of aggregation of great masses of diatoms, transformations took place which were favorable for each organism to make its minute contribution of oil.

VENTURA AVENUE OIL FIELD, VENTURA COUNTY, CALIFORNIA[1]

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Ventura, California

ABSTRACT

The Ventura Avenue oil field is located in Ventura County, California, 2½ miles north of the city of Ventura, in the Ventura River valley. This field has the reputation of being the most difficult field in California in which to complete a deep well. The topography of the field is very rough, embracing elevations from 100 to 1,100 feet. The Ventura anticline is 16 miles long with Ventura Avenue field at the center. The anticline plunges in both directions from the center of the field and is characterized by steep dips on the flanks, which range from 30° to 60°. Production comes from the Pico formation, of lower Pliocene age. The field has six oil zones, but practically all production comes from the deepest zone, the Lloyd. The Lloyd zone has a known thickness of 2,600 feet, with the bottom of the zone as yet not found. The Ventura Avenue field has at present [February, 1928] a production of 57,000 barrels per day of 29°–30° gravity oil, from 113 wells. The field has produced, since its discovery in 1915, up to January 1, 1928, approximately 44,000,000 barrels of oil and more than 130,000,000,000 cubic feet of gas, yielding approximately 1 gallon of gasoline per 1,000 cubic feet of gas, and should ultimately produce 250,000,000 barrels of oil and 600,000,000,000 cubic feet of gas.

INTRODUCTION AND LOCATION

The Ventura Avenue oil field[3] has only recently come into prominence as an oil-producing area, although the field has been producing oil for more than 10 years. The new general interest in this field is due to the greatly increased production in the past two years and the extreme depth and great thickness of the oil zones.

The Ventura Avenue oil field is situated on both sides of Ventura Avenue, the main highway leading from the city of Ventura to the Ojai Valley. The field is 2½ miles north of the city, in the Ventura River valley. This field, which has been so slow in development, will probably be one of California's great oil and gas producers. It has been the privilege of the writer to watch its development; from a field of 6 wells, producing 345

[1] Read before the Association at the San Francisco meeting, March 23, 1928. Manuscript received by the editor, April 4, 1928. Reprinted, with modifications, from *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 7 (July, 1928), pp. 721–42.

[2] Resident geologist, Ventura division, Associated Oil Company.

[3] For previous description, see L. C. Decius, "Natural Gas Development in California," *Oil and Gas Jour.* (June 16, 1927), pp. G-75, 76, 79, 80, 84, and 88.

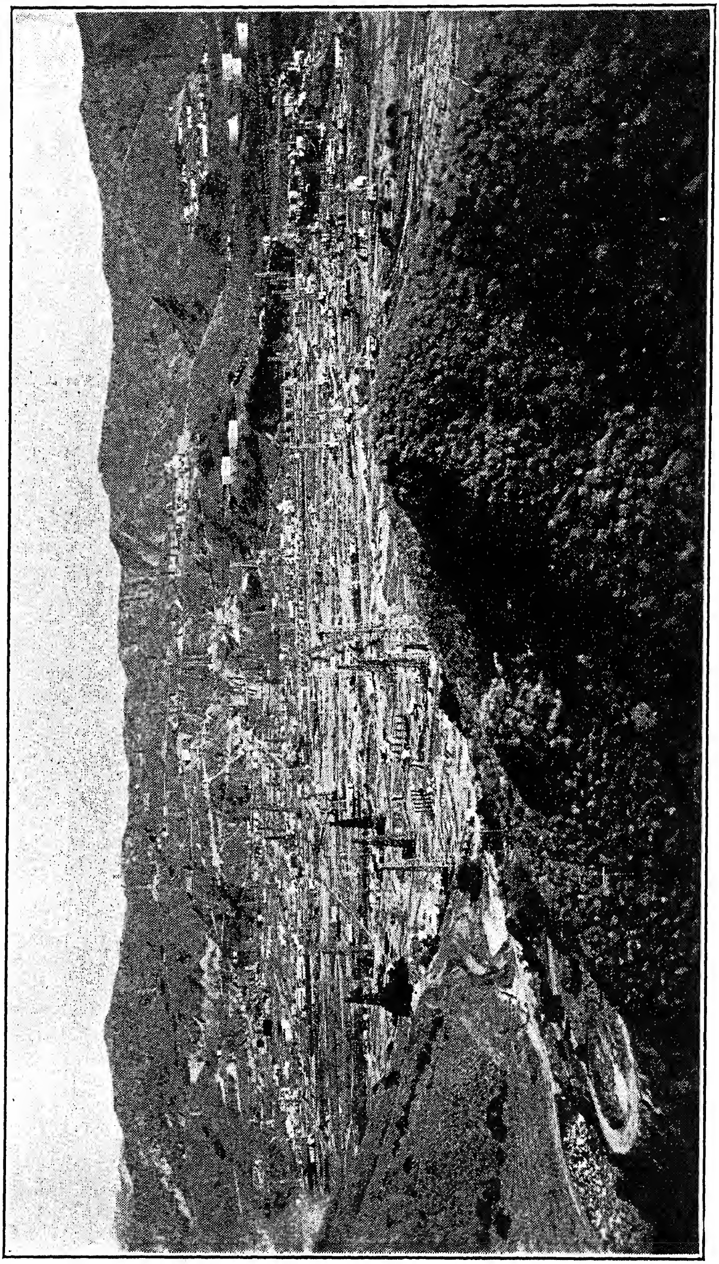

FIG. 1.—View of Ventura Avenue oil field taken in January, 1928, looking east across Ventura River from the Shell Company's Taylor lease to the Associated Oil Company's Lloyd lease.

barrels per day in August, 1921, to a production of 60,000 barrels of oil and 220,000,000 cubic feet of gas per day, from 72 wells in November, 1926. Figure 1 shows a view of Ventura Avenue oil field taken in 1928, looking east across Ventura River from the Shell Company's Taylor lease to the Associated Oil Company's Lloyd lease. Figure 2 shows the location of Ventura Avenue and Rincon oil fields on the Ventura anticline.

To one who has not been associated with the operations in the Ventura Avenue field, it is difficult to realize the obstacles that nature has set in the path of development of this field. The hard, shifting, and squeezing formations must be penetrated to great depths, in the face of tremendous gas pressures, to reach the best producing zone. As a result of these difficulties, the Ventura Avenue field has the reputation of being the most difficult territory in California in which to complete a well. Nor is the task completed, for the bottom of the producing sands has not yet been reached.

TOPOGRAPHY

Although the Ventura anticline is situated in an area of relatively recent physiographic development, the topography gives but slight indication of the presence of a fold of such magnitude. There is no evidence of an anticlinal ridge, nor is there any pronounced line of uplift along the axis of the structure. The anticline is dissected at the surface by eleven stream courses varying in magnitude and direction, the most conspicuous being the canyon of Ventura River. Near the dome of the anticline, along Ventura River, the major streams cut across it at right angles without being affected by the geologic structure. However, streams that cut the anticline farther down the plunge, on either side of the dome, are influenced by the folding, and swing in a curve around the nose of the structure.

The highest elevation in the present productive area is approximately 1,150 feet above sea-level, although extension of the field toward the east and west may overlap elevations in excess of 1,500 feet. The lowest elevation in the field is 100 feet, where Ventura River cuts, at right angles, through the anticline.

There are approximately 300 acres of flat land in the field in the Ventura River valley, where the anticline is structurally the highest. The other 900 acres of practically proved leases lie in the hills. This condition has necessitated cutting roads and rig grades on the steep hillsides. The construction program has required the moving of nearly 2,000,000 cubic yards of sand, shale, conglomerate, and hard sandstone for roads, rig grades, tank grades, and sump holes. One rig grade in particular required

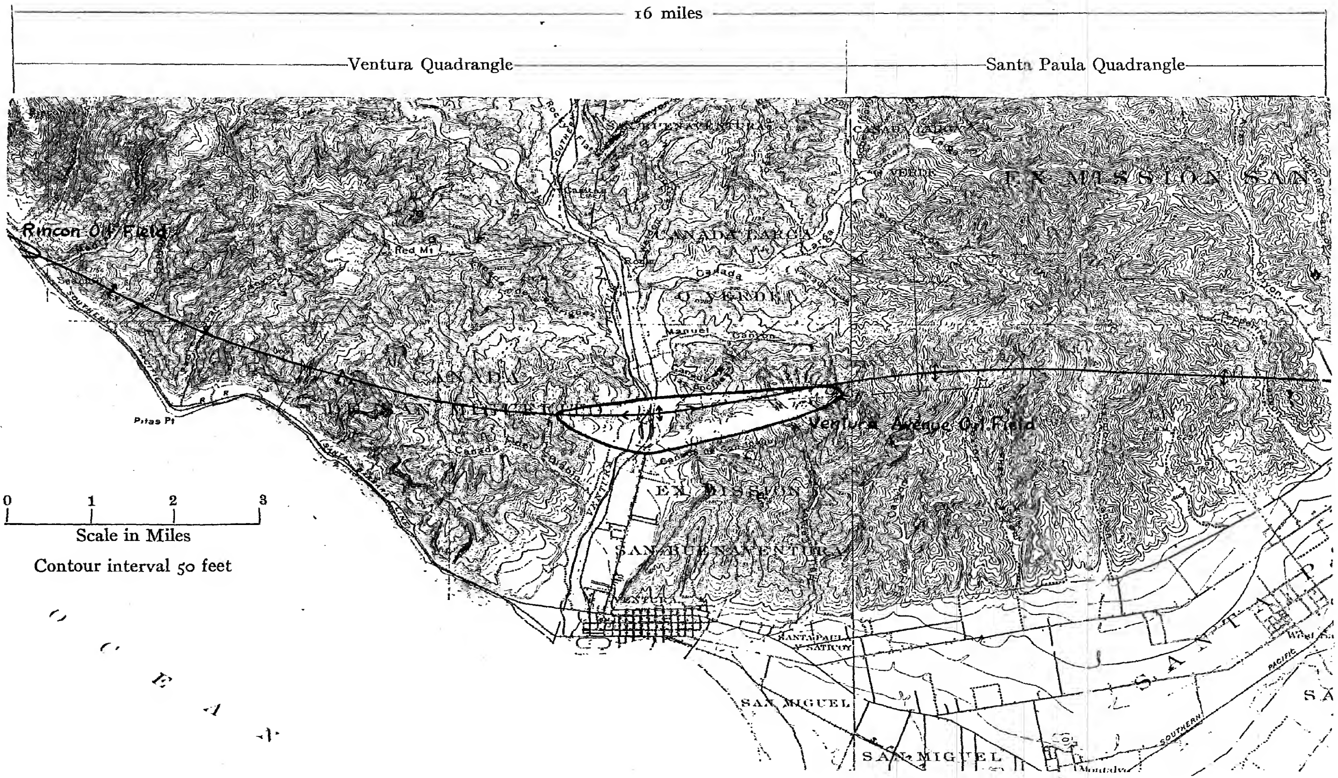

FIG. 2.—Map showing position of Ventura Avenue and Rincon oil fields on tb Ventura anticline (U. S. Geol. Survey).

the excavation of a 90-foot cut and the moving of 35,000 cubic yards of material.

STRUCTURAL GEOLOGY

The Ventura Avenue field is on the structurally highest part, and nearly at the center of the large and perfectly closed Ventura anticline, a sharp and well-defined fold, approximately 16 miles long and extending generally east and west. It is traceable from the center of the field 8 miles east, to a point where it plunges into the Santa Clara Valley, and 8 miles west, where it enters the Pacific Ocean. Figure 3 shows a view of Ventura anticline 4 miles west of Ventura River.

Figure 4 shows a view looking east into Hall Canyon and gives an idea of the many outcrops of the structure.

The structure is characterized by steep dips which range from 30° to 60° on the flanks of the anticline. East of the center of the field, the anticline has an average plunge of 3° E. for $1\frac{1}{2}$ miles to a structural terrace, whence it continues at an angle of 8° E. West of the center of the field it plunges 3° W. for approximately 3 miles, and flattens for some distance, but no exact low point can be determined. At some point, however, within this uncertain area, there is a low point, for where the anticline enters the ocean at the new Rincon oil field the structure is again rising.

Although the anticline is practically symmetrical, in the center of the field it is not constantly so. For example, $1\frac{1}{2}$ miles east of the center of the field, in Hall Canyon, in the vicinity of the Associated Oil Company's Lloyd No. 101, the axial plane has a pronounced south dip, amounting to 600 feet or more in 5,000 feet of depth. Beyond this point, toward the east, the structure seems gradually to resume its symmetry. West of the center of the field the axial plane dips north.

The subsurface structure as shown by the subsurface contour map on the base of the Gosnell shale (Plate 1), is a nearly perfect anticline very similar to the one mapped by the outcrops. The plunge in both directions, from the apex in Ventura River and the structural terrace in Hall Canyon, is again noticed in the subsurface map. The steeper dips on the north side of the axis east of the field, which give the axial plane a hade toward the south, and the reverse situation west of the center of the field, are also illustrated by the subsurface contour map. The present proved area, between the Shell Company's Taylor No. 16 and the Associated Oil Company's Dabney Lloyd No. 1, shows closure of approximately 400 feet. The other parts of the structure both east and west will show a closure of more than 1,000 feet, though not all of this will prove to be commercially productive.

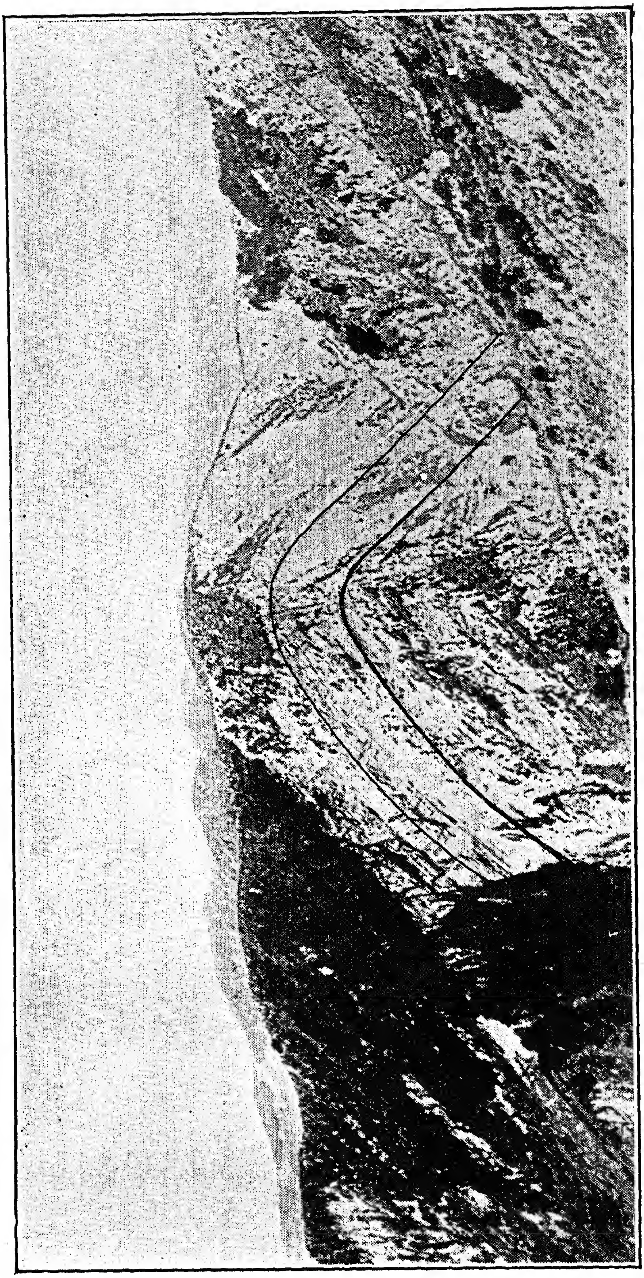

FIG. 3.—View of Ventura anticline 4 miles west of Ventura River.

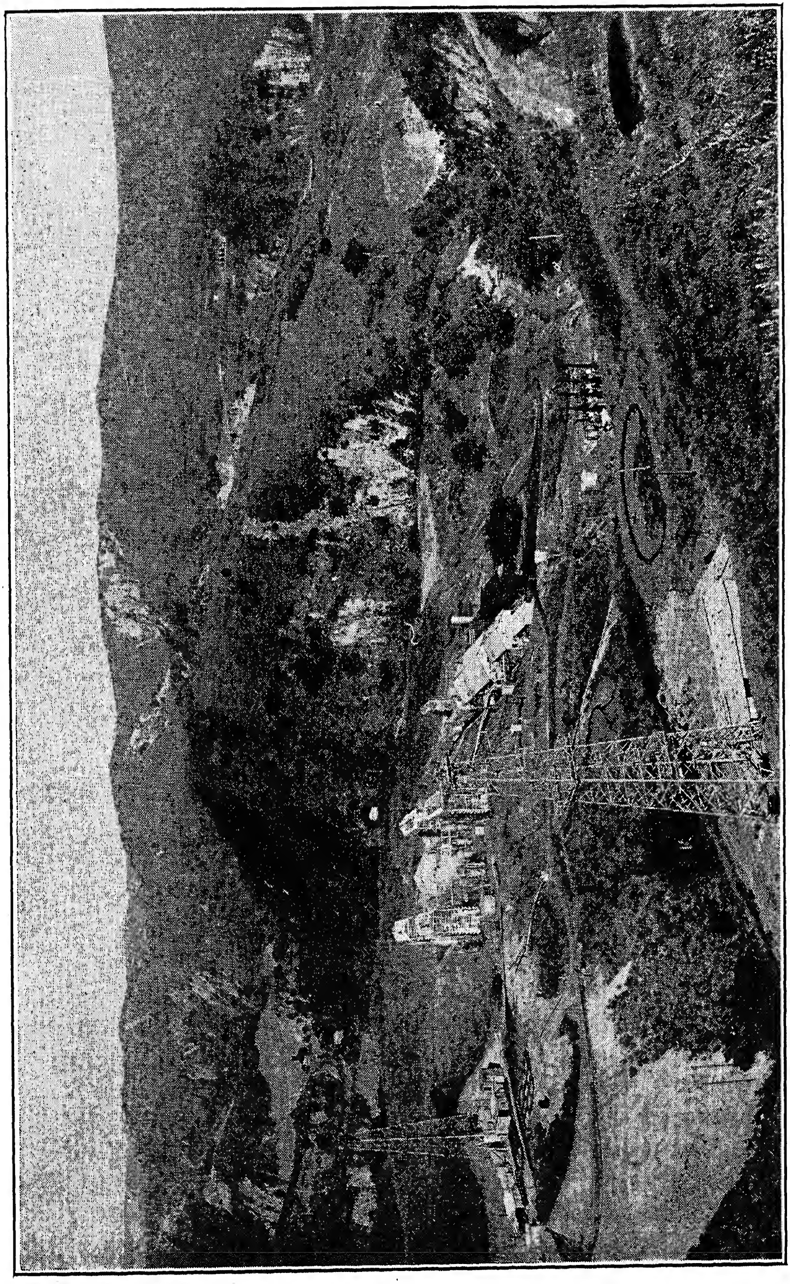

FIG. 4.—View looking east into Hall Canyon, showing many outcrops which are common along Ventura River.

The large drainage area of this structure is a contributing factor to the amount of oil found in the Ventura anticline. As the anticline has only one major dome, from Padre Juan Canyon on the west, to Aliso Canyon on the east, this great amount of oil is in one reservoir. The drainage area extends 1 mile north of the axis and at least 3 miles south of the axis for a length of 14 miles. The area on the north is cut off by a syncline and a fault. Though there may be a still greater area on the south side, this cannot be determined because of the alluvial covering of the Santa Clara River valley and the Pacific Ocean.

FORMATION AND OIL ZONES

All of the present drilling and production in the Ventura Avenue field is in the Pico formation (lower Pliocene) of the Fernando group (Fig. 5). In the Ventura region the Fernando is composed of the Saugus and the Pico formations, which have a total thickness in excess of 15,000 feet in the vicinity of the Ventura anticline. The strata penetrated consist of fine- to coarse-grained sand ranging from loose-running sands to extremely hard sand, sandy shale, and a lesser amount of blue, gray, and brown shale, in much of which *Foraminifera* are plentiful. The predominating sediment found in the lower oil zones, however, is a medium-to-fine sand that grades in many places into a very fine or "flour" sand.

Six different producing zones in the Ventura Avenue field are known, but at only one point (the Gosnell shale zone) is there a definite marker between them. The difference in the quantity and quality of the production and the areal extent of the zones are the only criteria for differentiating them. Even at the Gosnell shale zone it is not everywhere possible to differentiate because many parts of this zone are sandy. An approximate correlation may be determined from a study of the *Foraminifera.*

The first evidence of petroleum to be found is a gas zone on the crest of the structure and extending from a depth of 300 feet to 1,600 feet in fairly loose sands and sandy shales. This zone, although of no economic value at present, was once capable of supporting small commercial gas wells producing possibly 2 barrels a day of 56° Bé. gravity oil. It is now flooded and gives nothing more than approximately 1,000 barrels of salt water per day. This zone is of historic interest, however, on account of the fact that here the first clew to the oil deposits lying beneath was discovered.

Below the gas zone, the upper "Light-Oil" zone is gradually encountered, but with no marked change in lithology from the sands and sandy

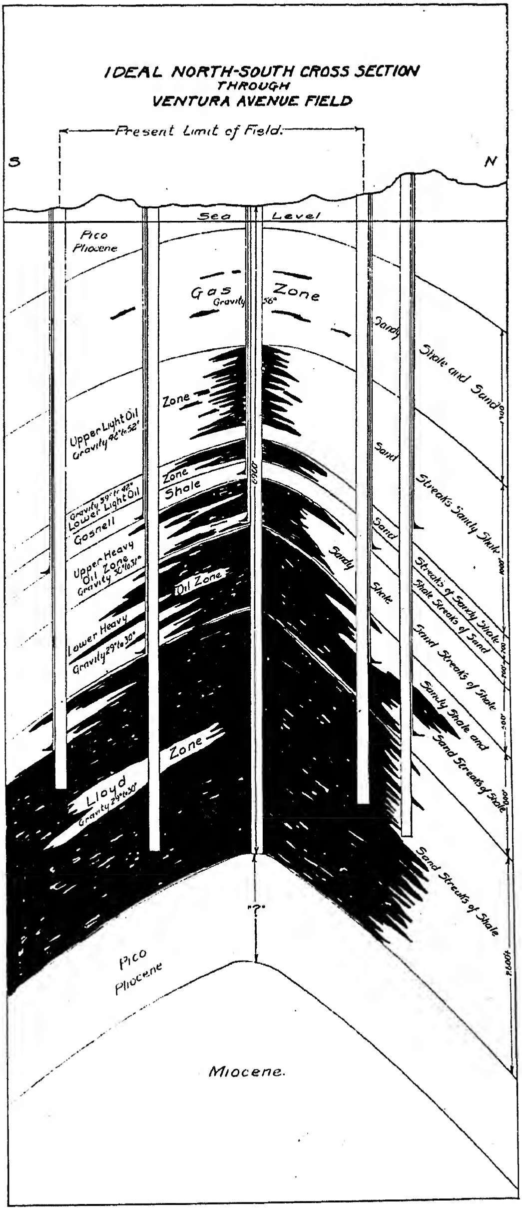

FIG. 5.—Oil zones in Ventura Avenue field. Depths shown in feet.

shales of the gas zone. This zone was originally capable of producing wells of approximately 150 barrels of oil varying from 48° to 52° Bé. gravity, with as much as 1,500 barrels of salt water and 200,000 cubic feet of gas. The zone extends from 1,600 feet to 2,600 feet in depth, although the best oil production occurs from 1,900 to 2,500 feet. The upper "Light-Oil" zone is now flooded with water, and very little oil is obtained from it. There are 3 wells in this zone whose present [February, 1928] average production is 13 barrels of oil varying from 48° to 52° Bé. gravity, 10,000 cubic feet of gas, and 270 barrels of water per day.

Below this zone, and overlying the Gosnell shale, is the lower "Light-Oil" zone. It consists of 200 feet of loosely consolidated sands and sandy shales, originally capable of producing wells of approximately 50 barrels of oil varying from 39° to 42° Bé. gravity and 100 barrels of water per day. This zone is also no longer of economical importance, as there is no production from it at present.

The Gosnell shale horizon, which consists of an irregular shale body streaked with sandy shale and sands, whose maximum thickness is 200 feet, is between the lower "Light-Oil" zone and the upper "Heavy-Oil" zone at a depth of approximately 3,000 feet in the center of the field. This horizon is the best marker in the field but in places is so sandy that it cannot be distinguished from the other zones, thus rendering correlation difficult.

The upper "Heavy-Oil" zone occurs below the Gosnell shale. It consists of 500 feet of sands and sandy shales, streaked with shale. This zone originally gave rise to wells not exceeding 150 barrels of oil varying from 30° to 31° Bé. gravity, 1,000,000 cubic feet of gas, and 60 barrels of salt water per day. The upper "Heavy-Oil" zone has probably been damaged to some extent by infiltrating water, although an effort has been made to protect it by cementing a string of casing above and below, and mudding the zone as it was penetrated. At present there is no production from this zone, but at some future time, when oil is not so plentiful as it is to-day, it will probably pay to drill wells for production from this zone on the top of the anticline.

The lower "Heavy-Oil" zone, immediately below the upper "Heavy-Oil" zone and extending for 800 feet with a similar lithological character, is capable of supplying considerably larger wells having initial productions of as much as 1,900 barrels of oil varying from 29° to 30° Bé. gravity and as much as 4,000,000 cubic feet of gas per day. It is free from water on top of the structure; but edge water, especially in the upper part of the zone, is encroaching on the flanks.

The deepest and richest of the zones has been named the Lloyd zone.[1] It has been so designated because discovered in the Associated Oil Company's Lloyd 9A. It comprises all of the oil zone below a point 1,300 feet below the base of the Gosnell shale, and to the present explored depth of 3,920 feet below the Gosnell shale, thus having a known thickness of 2,620 feet. Lithologically it is similar to the "Heavy-Oil" zones, but is characterized by its greatly increased productivity over any of the other zones previously mentioned, and by its considerably greater areal extent. However, in some of the wells now being drilled on the edge of the field, edge water is noticed in the top part of the Lloyd zone.

The Lloyd zone has supplied wells with initial productions of as much as 5,700 barrels of clean oil per day, and gas wells on the top of the structure have shown initial gas productions of 45,000,000 cubic feet per day and initial flow pressures as high as 1,100 pounds per square inch. This zone is entirely free from water, except as previously mentioned on the edge of the field.

Further drilling will demonstrate greater thickness of the Lloyd zone and the Pico formation, below which probably productive Miocene formations lie. If oil sands are found in the Miocene formations, as they have been found in three of the Los Angeles Basin oil fields, substantial production may be expected from these sources.

The Modelo shale of Miocene age is considered by most geologists as the generating series for the oil in the Ventura field. It is thought that this oil originated in the organic Modelo shale and migrated into the overlying Pico formation.

During the process of upward migration, the heavier constituents were left in the lower strata while the lighter hydrocarbons migrated into higher members. Another theory advanced by a few local geologists is that the oil originated in organic shales within the Pico formation and accumulated in the adjacent or overlying sands, the lighter constituents accumulating in the upper sands of the structure. It may be that both were contributing factors in the accumulation of oil and gas in the Ventura anticline. However, the lack of exposures of Pliocene organic shale renders the latter explanation less tenable.

HISTORY OF DEVELOPMENT

The drilling of a water well in 1885, on the property of A. D. Barnard, now the General Petroleum Corporation's Barnard lease, brought about

[1] F. W. Hertel, "Ventura Is One of California's Greatest Oil Fields," *Oil Weekly*, Vol. 44, No. 11 (March 4, 1927), pp. 47 ff.

evidence relative to the possibilities of oil in this locality. This well was drilled to a depth between 200 and 300 feet, where brackish water, a small amount of gas, and scum of light-gravity oil were encountered. This was a surprise, as oil and gas at that time were not expected anywhere except near the great seeps in other parts of the county. Barnard erected a sign near the well with the following inscription, "Oil, Gas, and Salt Here." This was a source of amusement to passers-by for some time, none of them realizing that some day this very spot would be surrounded by oil derricks.

In 1898 R. B. Lloyd and E. A. Rasor, who had had geological experience in the Fullerton field, mapped the Ventura anticline. In spite of Lloyd and Rasor's favorable report on the field, no development work was commenced. Some time before this, two men by the name of Carpenter and Steinbeck bought the oil rights to all the property in the Rancho Ex-Mission San Buena Ventura, except that of tract "R," which later became the Lloyd ranch. Tract "R" was discarded as valueless by these men, because the anticlinal theory of oil accumulation had few followers at that time and because everyone was interested in the faulted structures where the oil seepages occurred.

In 1902 the new Weldon Oil Company drilled its Hartman No. 1 in Sec. 22, T. 3 N., R. 23 W., S. B. & M. This well was drilled near the axis of the anticline a short distance east of the dome but reached a depth of only 750 feet. Some gas was encountered, but mechanical difficulties caused abandonment of the well.

Later, in 1903, interest was again directed to gas seepages in the Ventura River bed near the dome of the structure, which caused the Ventura County Power Company to drill a well in Sec. 28, T. 3 N., R. 23 W., to a depth of 400 feet, thereby discovering a shallow gas zone. Nine wells in all were drilled shortly after this to depths ranging from 400 to 800 feet, for the purpose of supplying gas for domestic use in Ventura and Santa Paula. Although the productions of these wells varied from 10,000 to 15,000 cubic feet of gas per day and a barrel or two of oil of 56° Bé. gravity, the large amount of water in the wells, and the difficulty in drilling them in the river bed with primitive cable-tool rigs, caused the abandonment of the enterprise, and Ventura returned to the use of artificial gas. The casing of some of these old gas wells may still be found in the Ventura River bed, and on top of the water in all of them is found a small amount of high-gravity oil. In spite of the actual production of gas from the structure, it was with difficulty that any capital could be secured for oil prospecting

in the field. In 1913, however, Ralph B. Lloyd was able to interest J. B. Dabney and E. J. Miley of the State Consolidated Oil Company.

In January, 1914, Lloyd No. 1 was spudded in by the State Consolidated Oil Company. After many difficulties, this well was drilled into the upper "Light-Oil" zone at a depth of 2,558 feet, at which depth, in July, 1915, the well blew out, wrecking the derrick and spraying gas, oil, and water. Though this ruined the well as a producer, it definitely established the presence of oil in the Ventura anticline.

About the same time that the State Consolidated Oil Company commenced on the Lloyd lease, Lloyd and Dabney commenced drilling on the Taylor lease, west of Ventura River. This partnership, using the facilities available at that time, drilled 3 wells, but none of them below 1,000 feet because of inability to cope with the heavy gas pressures. After their unsuccessful efforts, Lloyd and Dabney transferred their leases to the Shell Company of California in June, 1916.

Later, other wells were drilled into this light zone, some of which produced for a time. One produced as much as 100 barrels per day. Great difficulties were experienced in attempting to produce from this zone because of lack of a suitable clay, or shale, in which to cement a water string to shut off the large flow of upper water. It also was found that water occurred within the oil zone, which soon became flooded. Also, excessive gas pressures in this zone made drilling very hazardous, as several severe gas blow-outs occurred during the drilling. The wells blew out, destroying the rig and subsequently forming craters varying from 75 to 100 feet in diameter, full of oil, mud, and water, with the gas continuously bubbling through them. One well, upon being shut in, broke out at the surface 400 or 500 feet from the well, where a geyser of water, mud, oil, and gas shot into the air 8 or 10 feet, until again released at the well.

With improved drilling methods and a better understanding of local conditions, an important advance was made when the Shell Company was able to drill its Gosnell No. 1 through the Gosnell shale into the upper "Heavy-Oil" zone at a depth of 3,495 feet in April, 1919, and gave the field a 135-barrel producer. But this zone contained water; and, as the wells were costly, they were not great money-makers. Therefore, after drilling a few wells to this zone with no better success than that of the first venture, the Shell Company prospected further. This time, after cementing off the water and oil in the upper "Heavy-Oil" zone, the Shell Company drilled into the top of the lower "Heavy-Oil" zone, and in November, 1921, brought in a clean well in Taylor No. 3 at a depth of 3,737 feet, with

an initial production of 400 barrels per day. This was followed by greater successes through the deeper penetration of the lower zone. When, in March, 1922, the Shell Company's Gosnell No. 3 was brought in, at 3,855 feet, it was a 939-barrel producer. The Associated Oil Company, which had acquired the State Consolidated Oil Company's property in June, 1920, brought in Lloyd No. 5 in October, 1922, at 4,051 feet, a 1,900-barrel well, which had penetrated the lower "Heavy-Oil" zone a little more than 300 feet. Several wells were drilled into this oil zone, and a few satisfactory wells were completed, extending the known thickness of the lower "Heavy-Oil" zone to 800 feet.

In spite of the satisfactory producers in the lower "Heavy-Oil" zone, the operators in the Ventura field were not satisfied; and in January, 1925, the Associated Oil Company brought in Lloyd No. 9A at 5,150 feet, producing from 700 feet of the lower "Heavy-Oil" zone and from 300 feet of the Lloyd zone. This well made 4,639 barrels of oil of 30° Bé. gravity, with less than 1 per cent water, and with 15,000,000 cubic feet of gas. This was more than double the production of any previous well in the field. Three years after completion, this well was still flowing clean oil at the rate of 250 barrels per day, having produced more than 1,000,000 barrels of oil in the first 22 months of its existence.

It has been followed by many producers from the Lloyd zone, which has now been prospected to a depth of 2,600 feet, and the bottom not yet reached. To date this zone has given the field 108 producers varying in production from 1,000 to 5,700 barrels and ranging in depth from 4,700 feet to 7,100 feet.

Besides the deeper penetration of the Lloyd zone, another important development was the completion of Lloyd No. 101 in Hall Canyon, by the Associated Oil Company in March, 1926. This well was a 1,600-barrel producer at 5,392 feet and extended the field a mile beyond the limits of production at that time. With the extension of the field toward the west by the Shell Company's Taylor No. 16, and on the east by the Associated Oil Company's Dabney-Lloyd No. 1, the field at present shows a proved area 3 miles long and $\frac{3}{4}$ mile wide at the widest point, and its size will probably be considerably increased.

The leases in the Ventura Avenue field have been held in large blocks by the Associated Oil Company, Bolsa Chica Oil Company, General Petroleum, Petroleum Securities Company, and Shell Company. Until 1925 the Associated Oil Company, General Petroleum Corporation, and the Shell Company were the only operators in the field. Since then the Bolsa Chica Oil Company and Petroleum Securities Company have taken

leases on the flanks of the structure. At that time these latter holdings seemed doubtful of production, but they are now rewarding these operators in good measure for their efforts. Beyond the limits of production down the plunge of the anticline on the east in Sexton Canyon, 4 miles from the center of the field, the Milham Exploration Company drilled a well to 7,092 feet without obtaining any important showings. This seems to limit the field on the east, although deeper drilling may discover productive sands. On the west the Associated Oil Company drilled its Taylor No. 1-A in Diablo Canyon, 2½ miles from the center of the field, to a depth of 5,215 feet, with no important showings. Deeper drilling, however, may prove the structure productive at this place. On the north, G. J. Magenheimer drilled a well to 7,320 feet, with no commercial production secured. This seems to limit the field in this direction. However, the Star Petroleum Company is drilling a well east of the Magenheimer well, which may extend the field in that direction. On the south flank of the field, south of the Petroleum Securities Company leases, the M. K. T. Oil Company is drilling a well which may extend the field down the south flank.

PRESENT STATUS OF FIELD

The field at present [February, 1928], is producing from 113 wells approximately 57,000 barrels of oil that has a gravity varying from 29° to 31°, 213 million cubic feet of gas, and 4,500 barrels of water per day. This shows a daily average per well of 504 barrels of oil and 1,885,000 cubic feet of gas. Of the present 113 producing wells in the field, 102 are flowing and 11 pumping. There are 52 wells 6,000 feet or more in depth, 18 are 6,500 feet or deeper, and 5 wells more than 7,000 feet. The average depth of the 113 wells is 5,650 feet.

Since November, 1926, when the peak of 60,000 barrels per day was reached, the production in the field has remained between 50,000 and 60,000 barrels per day, except for the months of May to August, 1927, when the field was shut in 33⅓ per cent to curtail overproduction (Fig. 6).

Production per acre is at present rather difficult to estimate because the field has much proved area as yet undrilled. However, the General Petroleum Corporation's 12½-acre Notten lease gives an idea of the productiveness of the sands in the Ventura Avenue field. This lease is near the center of the field, which is almost completely drilled except in zones below those already discovered. At present it shows a recovery of 330,000 barrels per acre and should ultimately produce 375,000 barrels per acre. The field as a whole, within the zones now known, can not be expected to run as high as the Notten lease as there are some parts that are not nearly

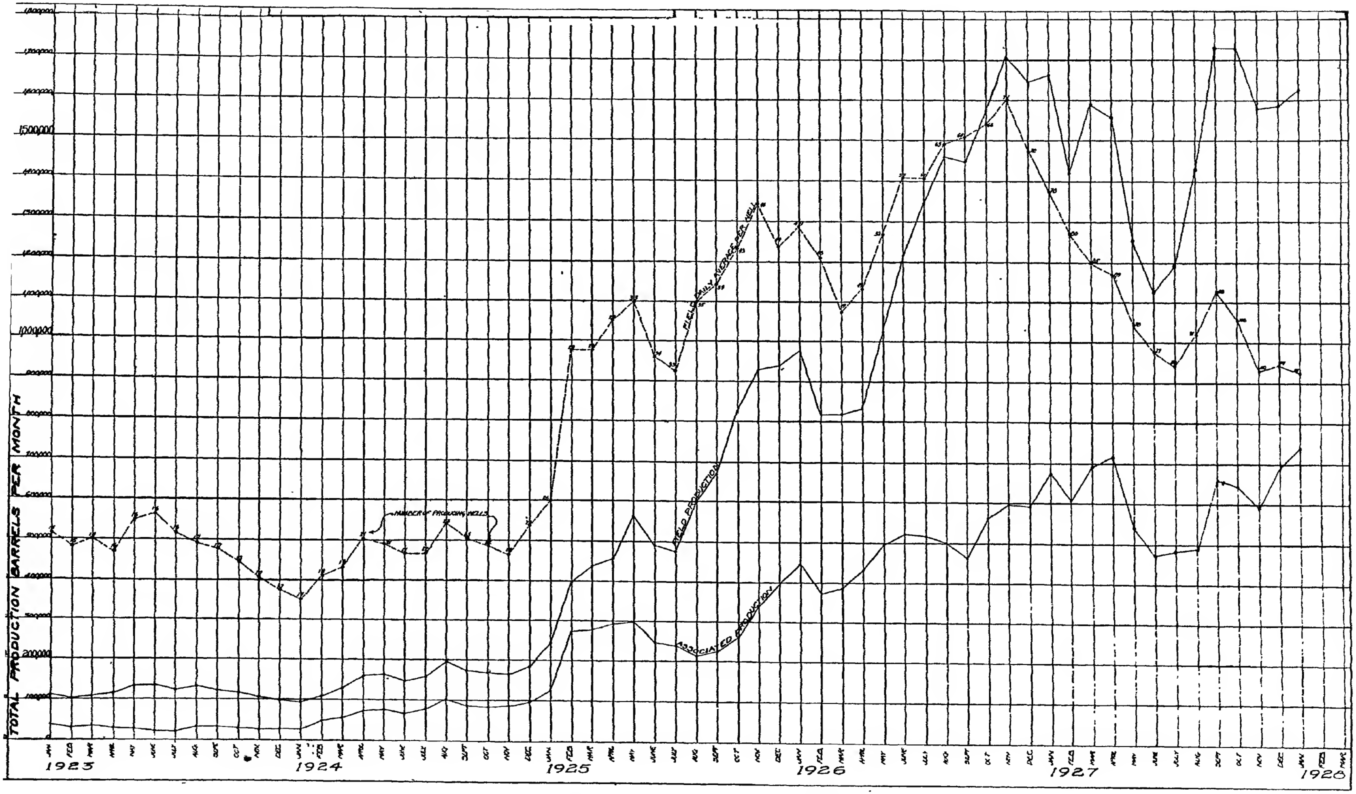

FIG. 6.—Chart showing monthly oil-production curve of Ventura Avenue field.

so productive, but the field should give an ultimate production of more than 200,000 barrels per acre.

An analysis of Ventura Avenue crude oil by Egloff and Morrell[1] shows the following properties:

A.P.I. gravity	29.5°
Furol viscosity at 77° F.	14 Sec.
Cold test	22° F.
Sulphur	1 per cent

Products derived from the crude oil:

	Percentage
Gasoline	31.0
Kerosene	7.2
Gas oil	19.8
Lubricating oil	12.3
Paraffin wax	2.7
Pitch bottoms	25.0
Water	2.0

It was further stated that experiments showed a possible yield of 68.6 per cent gasoline from the crude by combined topping and cracking operations.

The oil is taken out by pipe lines to the Pacific Ocean at Ventura, where it is loaded on tankers, either from the wharf or through a submarine pipe line laid on the ocean bed a half mile into the sea.

The gas-oil ratio in the Ventura Avenue field at present [January, 1928] is slightly less than 4,000 cubic feet per barrel of oil. In the earlier history of the field the gas-oil ratio was approximately 1,000 cubic feet per barrel but has gradually risen to the present figures.

The gas-oil ratio of the wells depends approximately on their position on the structure, being greatest in those near the top of the structure, decreasing in the wells farther down the flanks of the fold.

Although the wells of greatest gas-oil ratio are on the axis of the anticline, they are approximately 3,000 feet east of the dome of the anticline. Thus the gas crest and the structural crest do not coincide. Some wells near the top of the structure have had gas-oil ratios as high as 30,000 cubic feet per barrel of oil, and others on the flanks of the anticline show as low as 500 cubic feet per barrel of oil.

[1] Gustav Egloff and Jacques C. Morrell, "Refining of Ventura Avenue Crude," *Oil and Gas Jour.*, Vol. 26, No. 8 (July 14, 1927), p. 130.

The general analysis of the gas in the Ventura Avenue oil field is as follows:

	Percentage
Methane	83.0
Ethane	12.0
Propane or heavier	4.0
Carbon dioxide	0.8
Oxygen, hydrogen, and nitrogen	0.2

Gasoline is extracted from the gas at absorption plants on the leases. Approximately 1 gallon of gasoline per 1,000 cubic feet of gas is recovered.

TABLE I

Year	Production (Barrels)	Average per Day (Barrels)	Number of Wells
1917	1,155	3	1
Total	1,155		
1918	18,949	52	4
Total	20,149		
1919	40,285	110	4
Total	60,434		
1920	106,737	319	8
Total	167,171		
1921	132,440	363	12
Total	299,611		
1922	710,987	1,948	18
Total	1,010,598		
1923	1,409,110	3,861	22
Total	2,419,708		
1924	1,836,445	5,018	30
Total	4,256,153		
1925	7,020,189	19,233	53
Total	11,276,342		
1926	14,862,805	40,720	82
Total	26,139,147		
1927	17,859,688	48,931	123
Total	43,998,835		

Some of the gasoline is shipped in tank cars and trucks to different refineries, but the Shell Company has a 4-inch gasoline line to its refinery at Wilmington, 80 miles away.

A small amount of dry gas is used in Ventura and the surrounding towns of Santa Barbara, Oxnard, and Santa Paula. A greater amount, however, is taken care of by two 12-inch pipe lines with a capacity of 30,000,000 cubic feet per day each and one 15-inch pipe line with a capacity of 50,000,000 cubic feet per day to Los Angeles, 80 miles south. Besides these outlets and the field use of the gas, there is still some surplus.

Up to January 1, 1928, the Ventura Avenue oil field had produced nearly 44,000,000 barrels of oil. Table I shows the production of the field by years to date.

FUTURE DEVELOPMENT

Future production depends upon the extension of the field beyond its present limits, upon the rapidity with which the controlling companies drill, and upon the depth to the oil sands. Although the writer does not believe that the Ventura Avenue field will ever have a phenomenally large daily production, probably never yielding 100,000 barrels per day, it is easily capable of reaching this figure with intensive drilling. Five years hence, however, or even ten, when the depth of Pico oil sands may have been determined, and with possible production from the Miocene formations, the Ventura Avenue field will still be a factor in California's oil production. The ultimate production cannot be predicted with any degree of certainty, but it may be safely said that it will be more than 250,000,000 barrels of oil and more than 600,000,000,000 cubic feet of gas.

SUPPLEMENT[1]

The chief development in the Ventura Avenue field subsequent to the paper given before the San Francisco meeting on March 23, 1928 was the completion of the M. K. & T. Oil Company's Foster No. 1 on July 4, 1928, at a depth of 5,736 feet, with an initial production of 2,040 barrels of 29° gravity oil per day. This well is at present (May, 1929) flowing at the rate of 450 barrels per day.

The completion of this well, which was 700 feet down the south flank of the structure from the farthest south producer at that time, proved practically the entire acreage of the Petroleum Securities Company. This caused the Petroleum Securities Company and the Pacific Western Oil Company, which purchased the Orton and Willett leases from the Petroleum Securities in November, 1928, to enter into an extensive drilling program on their property and this led to an offset campaign by the Shell Oil Company.

This drilling program resulted in maintaining the field production at a level which made the year 1928 the peak year of production to date in the Ventura

[1] May 24, 1929.

Avenue field, with a production of 18,994,659 barrels of oil, giving the field a total production of 62,993,495 barrels of oil to January 1, 1929.

Due to the completion of a considerable number of good wells in April and May, 1929, the peak production was reached in May, 1929, with a production of more than 63,000 barrels per day. However, as this resulted from the completion of several wells at one time, and from a conservation program now in effect in California, it is not expected that this amount of production will be maintained very long, but that the field will soon again maintain a production between 50,000 and 55,000 barrels per day, as it had for some time previous.

The field has been extended 800 feet westward from Taylor No. 16 by the Shell Oil Company with the completion of Taylor No. 23 with an initial production of 1,557 barrels per day and Taylor No. 34 is now being drilled 800 feet west of Taylor No. 23 to attempt to extend the field farther west. However, the east end of the field has not been extended, and the drilling has shown that the field is practically limited on the east by the Dabney-Lloyd No. 1 except for extremely deep drilling.

The Star Petroleum Company's well on the Canet property about a mile northeast of the Dabney-Lloyd well was abandoned as a dry hole at a depth of 6,773 feet.

There are several wells being drilled that may or may not extend the field beyond its present limits. The most promising of these wells is the Percy No. 1, on the M. K. & T. Oil Company's lease, being drilled by the Associated Oil Company. This well is 400 feet south of the M. K. & T. Oil Company's Foster No. 1. It encountered oil sand at 6,914 feet and is still drilling in shale and oil sand at 7,400 feet which should make a producer.

Seven hundred feet south of the Percy No. 1 the Penn-Kan Oil Company is drilling on the Francis lease, but at a depth of 6,900 feet has not as yet encountered showings of any consequence.

East of Ventura River, on the north flank of the field, the Petroleum Securities is drilling a well on the Hartman property adjacent to the old Magenheimer wells, on the theory that the deep well drilled by G. J. Magenheimer deviated down the north dip, thus failing to get substantial production.

West of Ventura River, about 2,000 feet north of the nearest producer on the north flank of the structure, the Shell Oil Company is drilling its Taylor-Lloyd No. 1 in an attempt to extend the field in that direction.

Another attempt for production is being made on the eastern end of the anticline by the Federal Petroleum Company, drilling a well 3,000 feet south of the abandoned Milham Exploration well at 7,092 feet.

The field has been extended a short distance south and west, but no wells have penetrated sands deeper than those mentioned in the preceding paper, so that the total thickness of the oil zone is not yet known.

The future of the Ventura Avenue field will probably be very much in accordance with the statement in the preceding paper. At present the outlook

seems to point to a production of more than 20,000,000 barrels of oil for the year 1929 and a yearly production between 15,000,000 and 20,000,000 barrels for several years to come.

TABLE II

CASING DATA, VENTURA AVENUE

Outside Diameter in Inches	Weight in Pounds per Foot	Depth	Total Weight in Tons	Company	Well
13 3/8	61	4,500	137.2	Associated Oil	Percy No. 2
11 3/4	54	4,500	121.5	Pacific Western Oil	Willett No. 5
10 3/4	45	4,700	105.7	Associated Oil	Lloyd No. 58
9	45	6,660	149.8	Associated Oil	Percy No. 1
8 5/8	36	6,465	116.5	Shell Oil	Gosnell No. 30
6 5/8	26	6,906	89.8	Associated Oil	Lloyd No. 100
5 3/4	22	8,006	88.1	Pacific Western Oil	Willett No. 5

TABLE III

PRODUCTION, IN BARRELS, VENTURA AVENUE

Year	Production	Average per Day	Number of Wells
Total to Jan. 1, 1928	43,998,836	....	....
1928	18,994,659	51,898	158
Total to Jan. 1, 1929	62,993,495	....	....

ELK HILLS, KERN COUNTY, CALIFORNIA[1]

J. R. PEMBERTON[2]
Los Angeles, California

ABSTRACT

The first drilling for oil in the Elk Hills commenced in 1910. The first well to produce oil was completed in June, 1911, at a depth of 4,000 feet. At the end of June, 1928, the total production was 96,199,914 barrels. The surface beds, aside from alluvium, belong to the Tulare formation of uppermost Pliocene age and are divided into upper, middle, and lower zones, altogether 730 feet of fresh-water sand, marl, and clay. The subsurface beds are thicker and, in addition to the lower Pliocene, include Miocene formations. Maricopa diatomaceous shale (Miocene) is supposed to be the source of the oil. Surface structure, reflected by topography, is an elongate dome with closure of 450 feet. Subsurface structure much steeper than the surface indicates a closed dome in the eastern field, in the western field, and in the Hillcrest area. Anticlinal conditions have influenced the accumulation of the oil and gas; but sand conditions, more than position on structure, have influenced the volume of production.

ACKNOWLEDGMENTS

This paper is a digest and summary of parts of a report on the Elk Hills which was made by the Pan American Petroleum Company in 1924 under the direction of Van H. Manning. The report was compiled by J. P. Smith, Frank M. Anderson, Harry Johnson, Thomas Cox, Lester C. Uren, and the writer, with the valued assistance of Frank O'Neil and R. K. Patterson. Especial thanks are expressed to E. L. Doheny for his original order to prepare that report and for permission to publish this summary.

Publications[3] of the California State Mining Bureau and of the U. S. Geological Survey have been freely used in the preparation of this paper.

HISTORY OF DEVELOPMENT

Drilling commenced in the Elk Hills in 1910. Eleven holes were drilled, and, aside from minor showings of oil and gas in some of these

[1] Read before the Pacific Section of the Association at the Los Angeles meeting, November 1, 1928. Manuscript received by the editor, October 23, 1928.

[2] E. L. Doheny interests.

[3] Ralph Arnold and Harry Johnson, "McKittrick-Sunset Oil Region," *U. S. Geol. Survey Bull. 406* (1910); "Natural Gas in the Elk Hills," *California State Min. Bur.* (1919); R. W. Pack, "Sunset-Midway Oil Field," *U. S. Geol. Survey Prof. Paper 116*, (1920); C. C. Thoms and F. M. Smith, "Notes on the Elk Hills Oil Field," *California State Min. Bur.* (1920); and L. W. Saunders, "Recent Developments in the East End of the Elk Hills Oil Field," *California State Min. Bur.* (1925).

holes, no production was found. The first well actually to produce oil was the Associated Oil Company's No. 1 in Sec. 26, T. 30 S., R. 23 E., which was completed in June, 1911, at 4,000 feet. One other well in Section 28, same township, came in as a gas well, and 20 dry holes were also drilled in that year. No further drilling was done until 1919, when the Standard Oil Company completed a 233-barrel well in its Hay No. 1 in Section 36, same township. Most of the drilling activity up to this time centered about the middle of the Elk Hills, but the following year the Standard Oil Company completed the first good oil well in its Tupman No. 1 located in Sec. 36, T. 30 S., R. 24 E., 6 miles east of the original Hay No. 1. This well came in, February 12, 1920, producing 5,420 barrels. It naturally started considerable activity, and 17 more wells were completed in this eastern area during 1920, with an average initial production of 3,925 barrels. Twenty-two wells were also completed in the western pool during 1920. During the following year 94 wells were drilled, of which only 7 were dry holes. In 1922, 62 wells were completed, with no dry holes.

At the end of June, 1928, the total production of oil in the Elk Hills was 96,199,914 barrels.

PHYSIOGRAPHY

The Elk Hills are 28 miles southwest of Bakersfield, Kern County, California (Fig. 1). They form a practically isolated topographic unit 17 miles long, east and west, and 7 miles wide at the widest part, rising out of the floor of the San Joaquin Valley. The elevation at the eastern end is 300 feet, and at the western end, 900 feet above sea-level. The highest elevation is 1,551 feet. The aspect of the hills viewed from a short distance is that of an exceptionally regular topographic dome intricately dissected by minor gulches and arroyos (Fig. 2). The topography is of the extremely youthful type and is all of post-Pliocene age. On the southern margin the smooth slope of the hills is broken by some steep secondary ridges extending approximately parallel with the main axis. There are no gulches longer than 4 miles, this being the greatest distance from the higher central points to either margin.

GENERAL GEOLOGY

Thrusting from the southwest has deformed the sediments on the west side of the San Joaquin Valley into innumerable folds with many faults roughly parallel with the axis of folds (Fig. 3). The basement complex of granites and allied rocks is exposed 25 miles south of the Elk Hills and probably underlies the oldest sediments rather close to the surface

less than 20 miles southwest. The deformation on the west side of the San Joaquin Valley is most intense near the well-known San Andreas

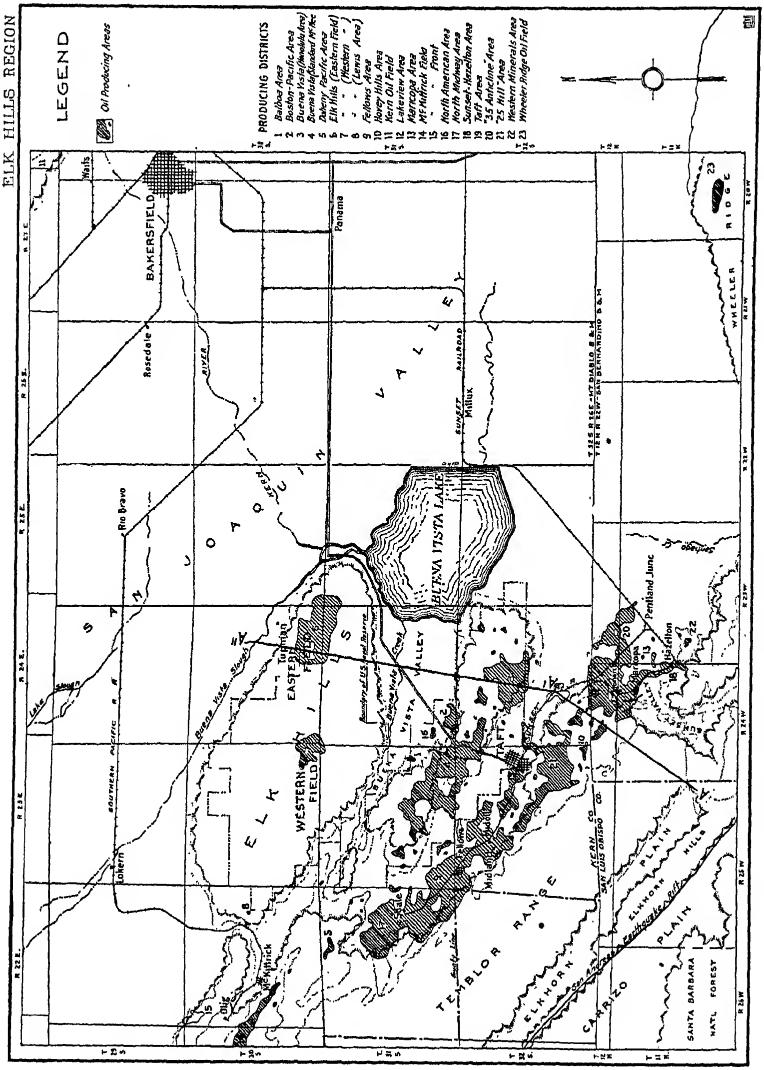

FIG. 1.—Regional map showing location of Elk Hills with reference to oil fields of Midway-Sunset region. Scale: width of one range, 6 miles.

fault which strikes northwest 20 miles southwest of the Elk Hills. The folds are farther apart and simpler farther away from the San Andreas fault, and the Elk Hills is the last fold exposed toward the San Joaquin

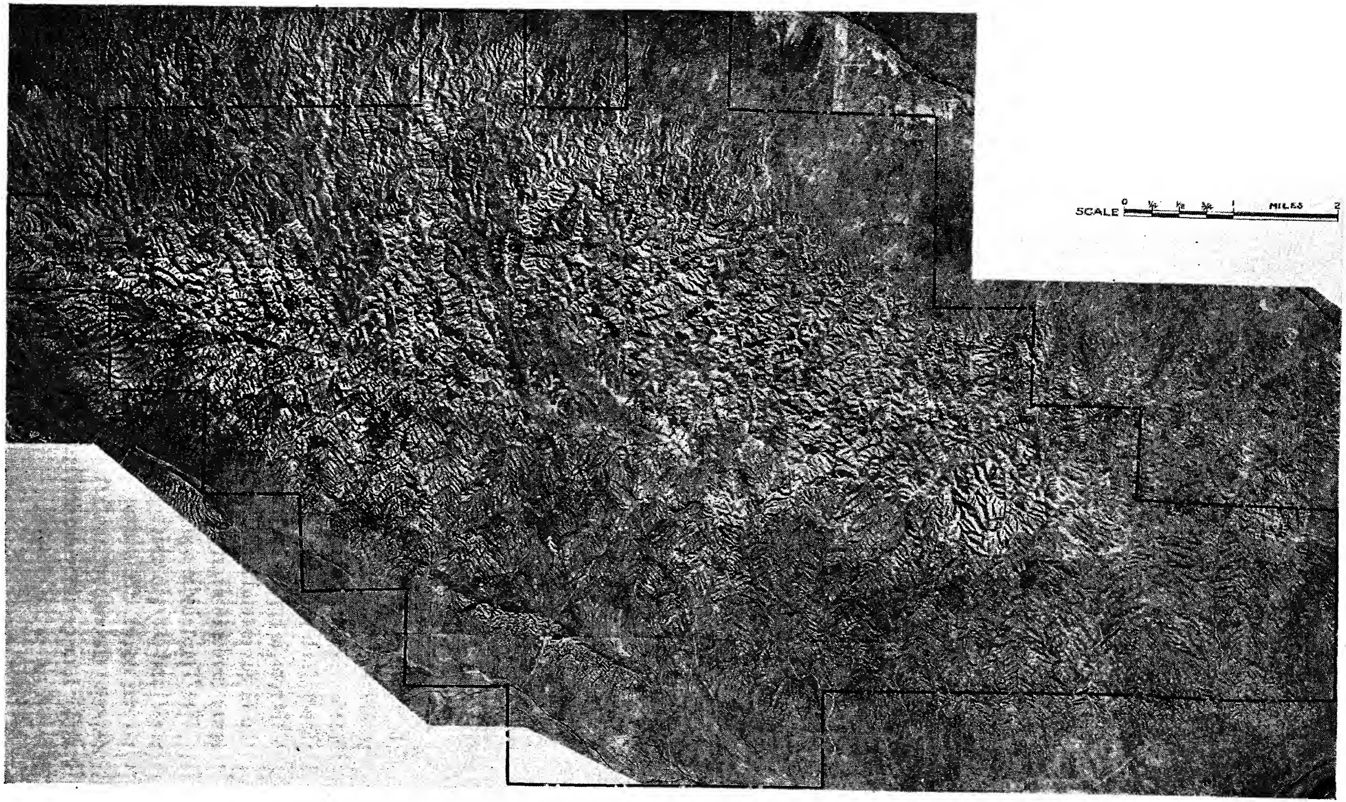

FIG. 2.—Aeromap of Elk Hills, California, showing Naval Reserve No. 1. Scale in miles.

Valley. Because of recognized overlaps and unconformities in the Tertiary sediments, it is known that this folding had its inception early in the Miocene and probably continued intermittently until the Pleistocene. All of the Pliocene beds are deformed, and the present structure of the entire area was probably completed after the Pliocene.

STRATIGRAPHY

Aside from alluvium surrounding the Elk Hills, the only exposed rocks belong to the Tulare formation of uppermost Pliocene age. These beds are the equivalent of the Paso Robles formation of the Salinas Valley and the uppermost part of the McKittrick group of Arnold and Johnson in the San Joaquin Valley. The Tulare formation consists of loosely consolidated gravels, gray, buff, and chalky sands; sandy shales, shales, marls, and clays, all of fresh-water origin. Approximately 730 feet of

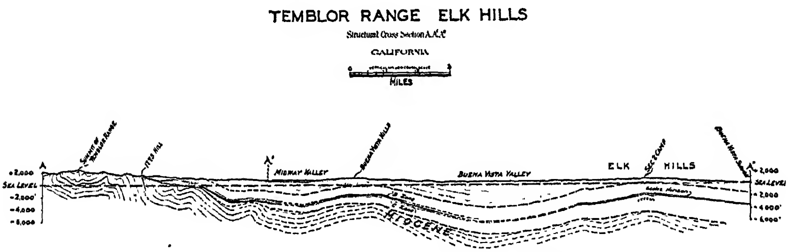

FIG. 3.—Cross section *A-A′-A″* of Figure 1, from Temblor Range north across Elk Hills. Depths shown in feet.

beds are exposed by erosion. This thickness may be divided into three groups.

1. The upper zone, ranging from 250 to 300 feet in thickness, is composed of tawny clay-shales with minor parts of sand and sandy shale near the top but grading into reddish and buff gravels and sands, in all of which fragments of Maricopa (Miocene) shale form a prominent part. The base of this zone has a persistent bed of reddish, heavy-bedded sandstone which was used as a key bed in plane-tabling the surface structure. This zone is exposed on the higher hills along the crest of the axis and on the ridges extending westward from the west end of the hills and on the lower flanks in nearly an unbroken belt surrounding the hills.

2. The middle zone contains buff and grayish banded shales, sandy shale, and clays in which gypsum is prominent and sands nearly absent,—no red colors. This zone is 210 feet thick. The beds of this zone are exposed throughout the Elk Hills except where covered by those of the upper zone or where erosion has cut through them into the lower zone.

3. The lower zone consists of nearly white and grayish clays and marls in which beds are very persistent and easily recognized. The beds of this zone are exposed only in the deepest gulches, where a maximum thickness of 215 feet has been measured. They have also been examined in a core taken from one of the minor sharp folds on the south flank of the hills.

Logs of wells and core samples indicate that the unconsolidated fresh-water sediments have a thickness ranging from 2,000 feet in the eastern end of the Elk Hills to 1,500 feet in the western end. One thousand feet below the base of the Tulare formation is a zone of uniquely widespread fossiliferous beds containing *Amnicola*, *Ostracoda*, and a strange fossil, called *Scalez*, which resembles a fish scale but which is supposed to be the operculum of a shell-less gastropod. The *Amnicola-Scalez* zone has been found in all parts of the Elk Hills where coring was done to locate it; also in the Buena Vista Hills, a similar structural unit 6 miles southwest of the Elk Hills; and in many places in the San Joaquin Valley as far as 50 miles toward the north. This particular fossil zone has been accepted in later years by petroleum geologists and engineers as indicating a point 1,000 feet below the top of the Etchegoin formation of lower Pliocene age.

The Etchegoin formation in the Elk Hills, although nowhere exposed, is shown by cores to consist predominantly of blue shales and sandy blue shales with many sands. The shales near the base are brown. There is a zone of sand beneath the *Scalez* zone in the eastern end of the Elk Hills which forms the principal producing oil sand of the area. Oil is found in the western producing area as deep as 2,750 feet below the *Scalez* zone but has not been tested to such a depth inside the producing area of the eastern field.

The full thickness of the Etchegoin formation is not known in the Elk Hills. The deepest well, 6,240 feet, probably penetrated 3,000 feet below the *Scalez* horizon, yet did not encounter recognized Miocene beds; thus, it seems probable that the Etchegoin is more than 4,000 feet thick.

Beneath the Etchegoin occur the Maricopa diatomaceous, silicious shales of Miocene age. This formation is known from measured sections, where exposed in the Temblor Range on the west, to range from 2,000 to 7,000 feet in thickness, but is commonly considered to be 5,000 feet thick. It is supposed to be the source of the Elk Hills oil.

SURFACE STRUCTURE

The surface structure (Fig. 4) is plainly evident in good exposures throughout the area and almost parallels the topography. Dips north, west, and south are slightly steeper than the slope of the hills, but toward

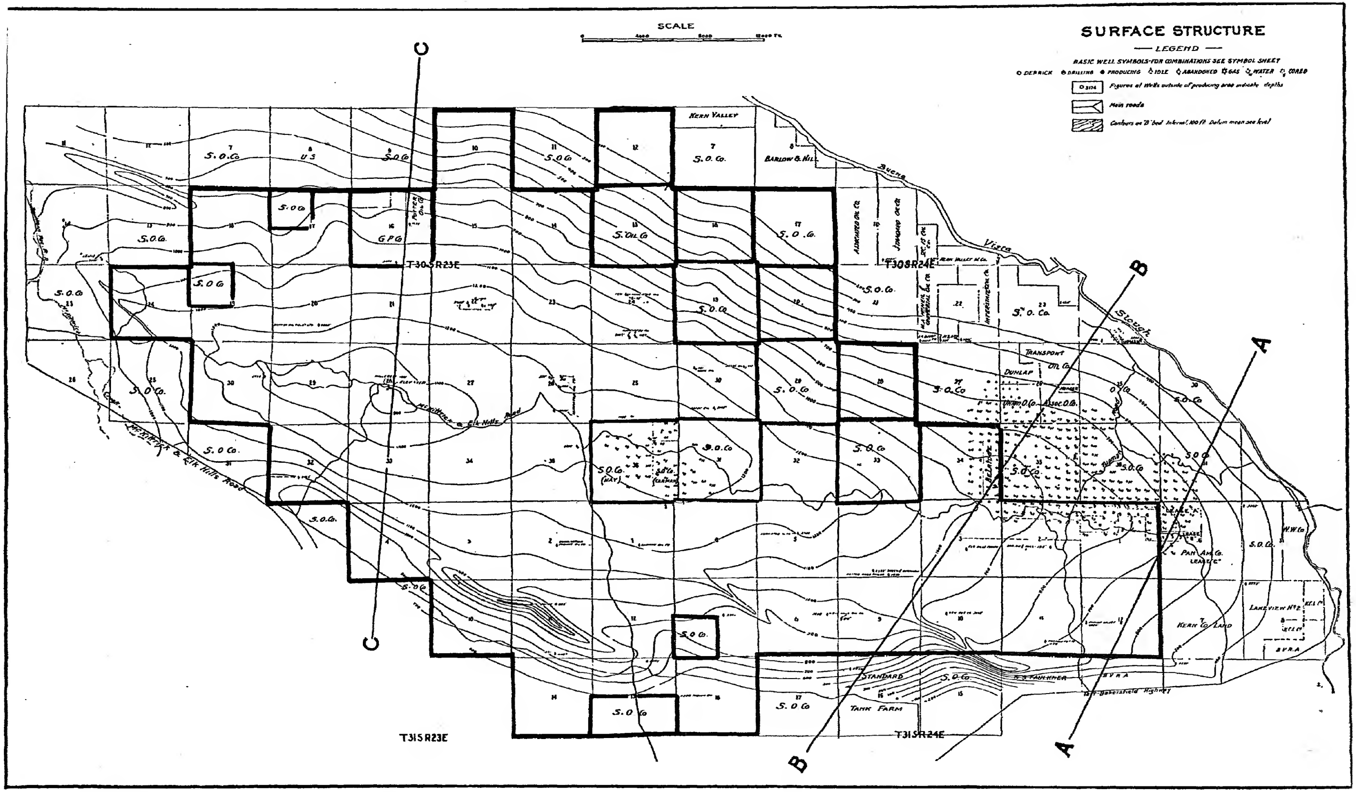

FIG. 4.—Surface structure of Elk Hills (Naval Reserve No. 1). Contour interval, 100 feet. Scale in feet. Cross sections have not been reproduced.

the east the dip is slightly less than the slope. The highest structural point corresponds exactly with the highest hill. The structure of the Elk Hills is a smooth elongate dome whose apex is at a point one-third the length of the hills from the west end. The axis trends along a line slightly south of the center line of the hills, this location being due to a longer north limb caused by lower valley floor on the north side. The total closure is only 450 feet, but the plunge eastward amounts to 1,250 feet, and toward the west, 700 feet.

This great dome is interrupted on its south flank by four small sharp anticlines with axes inclined approximately 20° away from the axis of the main hills and diverging eastward. The westernmost of these small folds has a closure of 300 feet, but the writer was unable to find closure in the other three folds, although the U. S. Geological Survey party, under W. P. Woodring, did find closure. Near the northwest margin of the hills is another small, sharply closed fold with nearly 75 feet of closure.

Faults of appreciable displacement are not in evidence anywhere on the surface. Rifts several miles long were detected in aerial photographic maps. When examined on the ground, these seemed to be nothing more than very slight tensional slips. All are on the northern flanks, or valley side, where drag against the uplift would be the longest. Two subsurface faults of 200 feet displacement, discovered in drilling, have no surface expression other than synclinal sag on the alignment of the fault.

Average dips on the north flank of the Elk Hills are approximately 3° near the axis but are as steep as 6° near the flanks. The minor anticlines have dips as steep as 70°, although most of the dips range from 35° to 45°. The eastward plunge of the main axis is approximately 3° from the central part of the hills and the same westward from the highest structural point. Between these two points there is a flattening of the axis with an east dip ranging from 1° to 2°.

SUBSURFACE STRUCTURE

The subsurface structure (Fig. 5) is known only where wells have been drilled since the discovery of commercial oil. The logs of wells drilled before that time are of no service in delineating the subsurface structure.

The subsurface structure has been determined by using the *Scalez* bed as a marker (Fig. 6). This horizon is parallel with the producing oil sand of the eastern field, but in the absence of any continuous sand in the western field no such parallelism exists. The subsurface structure indicates a closed dome in the eastern field, one in the western field, and one in the Hillcrest area.

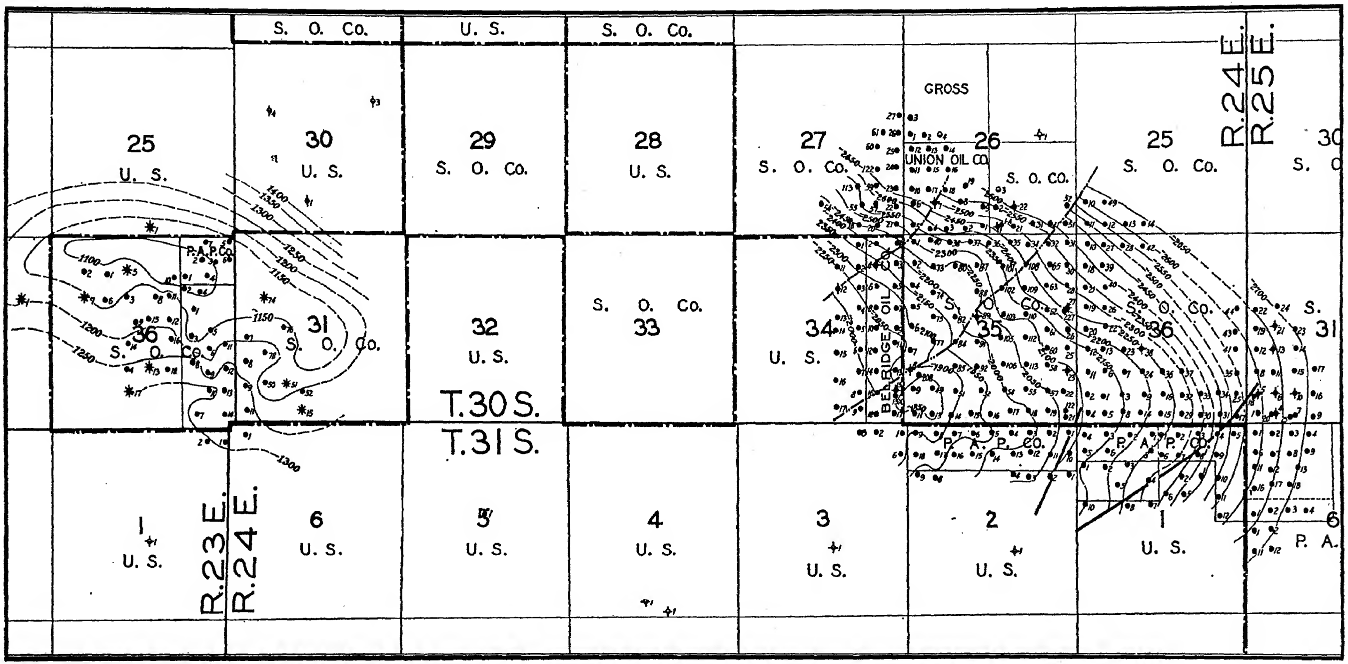

FIG. 5.—Subsurface structure of Elk Hills, western and eastern oil fields, drawn on *Scalez* zone. Contour interval, 50 feet. Scale: width of section, 1 mile. Location shown of four possible faults in eastern field. On June 30, 1928, the wells shut in were: those surrounding the Standard Oil Company of California's leases in western field; wells in Section 34 west of Belridge Oil Company's lease; wells in S. $\frac{1}{2}$, N. $\frac{1}{2}$, Sec. 2, T. 31 S., R. 24 E.; and the well in SW. $\frac{1}{4}$, SW. $\frac{1}{4}$, NW. $\frac{1}{4}$, Sec. 1, T. 31 S., R. 24 E.

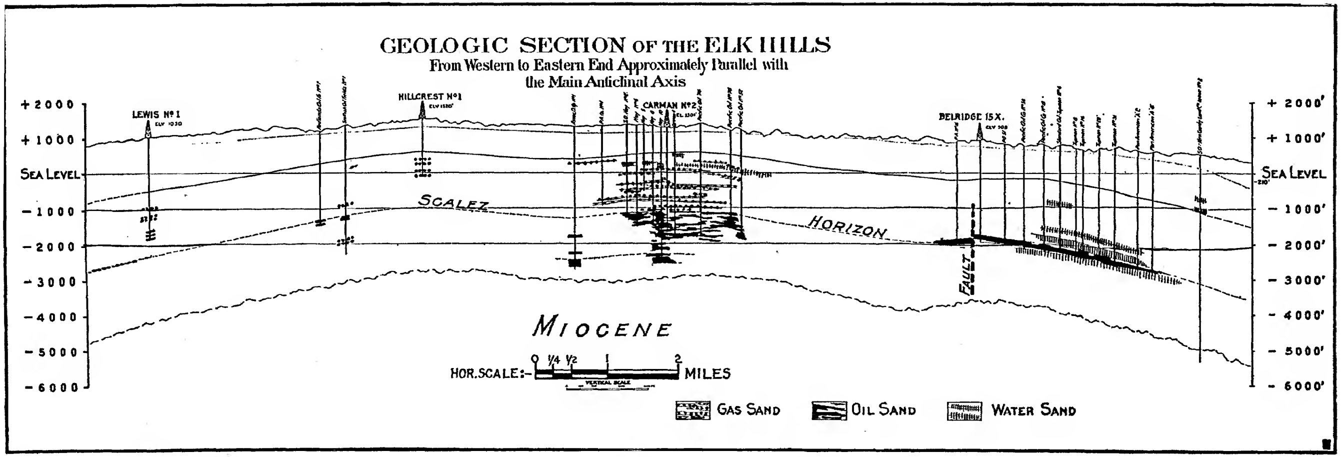

FIG. 6.—Longitudinal cross section showing surface and subsurface structure of Elk Hills. Depths shown in feet.

The subsurface structure in the eastern field is similar to that of the surface with the exception that the dips range from 30 to 45 per cent steeper. Between the high points of the eastern and western fields there is a difference of 500 feet in surface structural height, and a subsurface difference of 750 feet. It is very probable that a saddle exists between these two fields, but the location cannot be ascertained from either the surface or the subsurface structure in advance of drilling.

The subsurface structure of the western field is a dome with more than 100 feet of closure in the area so far drilled. Further drilling will probably prove more closure, thus indicating a saddle between this field and the Hillcrest dome, the highest surface structural point in the hills.

FAULTING

Two prominent faults have been discovered in Sections 25, 26, 34, and 35 in drilling in the eastern field. These are normal faults with a downthrow of 200 feet on the north or down-dip side. They strike northeast at an angle of nearly 45° from the main axis of the Elk Hills dome. They have no effect on production unless a well is completed in the fault plane itself, under which condition the hole is dry. Their extent is not known in advance of further drilling. They were probably caused by settling, following the uplift, on the valley side of the Elk Hills, and are thus similar to the minor surface rifts discovered along the lower flanks by means of the aerial photographs.

A third fault may extend across the north part of Section 1, although it is not definitely known. It seems to have a maximum displacement of 70 feet in the middle of the west line of Section 1 but diminishes to only a slight displacement in the northeast corner of that section. Its existence in Section 31 is not known. The displacement is the reverse of that on the two larger faults, the low side being on the south. A fourth fault may exist near the east side of Section 2 inasmuch as there is an oil sand containing oil of lighter gravity between this possible fault and the fault in Section 1. This productive sand is barren on either side of the supposed faults. There is also a difference in the production of wells in the main sand on either side of the fourth possible fault, the wells on its west side being much smaller.

It seems highly probable that many such faults will be discovered eventually in the slightly consolidated sediments of the large uplift of the Elk Hills.

OIL SANDS

Oil sands and sandy shales saturated with oil occur in the eastern field in a zone ranging from 150 to 200 feet in thickness. In 181 wells the

average thickness of saturated oil sand is 36 feet, and of saturated sandy shale, 45 feet. Beds of pure shale occur in the zone and separate the oil-bearing strata. The zone occurs directly beneath the *Scalez* dome and is, accordingly, of uppermost Etchegoin (Pliocene) age. The depth ranges from 2,800 to 3,400 feet, according to position with relation to structure and topography.

The sand is composed of quartz, with some feldspar and a little amphibole and pyroxene with no mica or magnetic minerals. Seventy-four per cent of the mineral content is lighter than 2.9 specific gravity. Fifty per cent of the grains are larger than 0.3 mm. in diameter. Porosity determinations gave figures ranging from 24 per cent to 35 per cent, and it is estimated that 28 per cent is probably an average. High porosities were obtained from flow-box samples, and low figures from compact core samples.

Another producing sand occurs in a part of the eastern field, overlying the *Scalez* horizon. Its physical characteristics are similar to the lower sand.

In the western field, sand conditions are quite different from those in the eastern field. Here lenses predominate, and drilling in search of prolific lenses has been conducted to depths stratigraphically 1,300 feet deeper than in the eastern field. Few lenses are traceable beyond a few wells. Differences in gravity of the oil also indicate a lack of interconnection of these lenses. The average penetration below the *Scalez* horizon of the 56 wells which have been drilled here is 503 feet, of which an average of only 11 feet is pure oil sand and 160 feet is sandy shales carrying oil, the remainder being barren shale. Some oil also occurs above the *Scalez* horizon.

Enormous gas wells have been completed in this field in sands as shallow as 1,800 feet, which are stratigraphically 800 feet above the *Scalez* horizon.

Studies of the physical properties of the productive sands from the western field were not made because drilling has not been done there for some time and no samples are available.

RELATION OF STRUCTURE TO ACCUMULATION

It is obvious that accumulation of oil and gas is induced by anticlinal conditions. With the exception of dry holes located exactly in fault zones in the eastern area, no dry holes have been drilled inside the field. Sand conditions influence the volume of production more than position on structure, and future development will be confined to a search for favorable sands.

On the subsurface structure map of the eastern area (Fig. 5) it is noticed that production occurs in a zone which plunges approximately 900 feet eastward in a distance of $2\frac{1}{3}$ miles, and that the top of this zone is 750 feet lower than the highest point in this zone in the western area. This would give a vertical enrichment of 1,600 feet if the lowest contour were to mark production around the entire field. This is obviously not possible because of the existence of numerous dry holes inside the location of such a contour. Thus the eastern area is defined by accumulation in favorable sands on the nose of a large dome, and the sands must pinch out toward the west. Initial and ultimate per acre production in the western area is so much lower than that in the eastern field that it might almost be stated that the accumulation came from the east and that the western dome contains the oil which has flowed past the spilling point on the eastern dome. The gas in this field and in one well on the Hillcrest dome also supports such an idea. However that may be, the productive sands and the most of the oil are in the eastern end of the Elk Hills, and the highest structural points of the hills are not nearly so productive, at least in levels so far tested.

In this part of California, productive beds have been encountered at depths of more than 1,000 feet in the Miocene, the top of which has not yet been discovered in the Elk Hills but is thought to be at a depth of approximately 6,000 feet in the eastern field. Thus, there are strata worth testing to depths of at least 7,000 feet. Oil, if obtained in these zones, may follow other rules for accumulation; and possibly the true crest, or Hillcrest dome, of the Elk Hills dome may carry this deep oil. In the Hillcrest dome the Miocene probably occurs at a depth of approximately 5,000 feet, if the known rate of convergence in the east continues westward.

The minor anticlines on the south flank of the hills have not been tested, but it is probable that some production may be found in the westernmost of these as it is the largest and most certainly closed.

GRAVITY AND PHYSICAL CHARACTERISTICS OF OIL

In the eastern area the gravity of the oil varies from 14.4° to 26.9° Bé. In more than half of the productive area and in more than three-fourths of the oil produced, the gravity is higher than 21° Bé. The oil of lower gravity is found on the north and east margins of the productive area, and the oil of highest gravity occurs in the wells located structurally highest.

In the western area the range of gravity is from 21.3° to 53.9° Bé., and the average is approximately 34°. Because of different depths at

which wells are completed, it is impossible to make any generalizations relative to the influence of structure on gravity. Many wells produce from several sands, and this fact further complicates the problem.

Great variation in physical character naturally occurs in oil ranging in gravity from 14.4° to 53.9° Bé., both in gasoline or other refinery cuts and in viscosity. The oils range in color from black to greenish black, and the gasoline content from 8 per cent to more than 30 per cent. Two grades are present, one of naphtha base and the other of mixed asphalt and paraffin base, the former being of lower gravity and carrying the lowest percentage of gasoline. The sulphur content in all of the oil is less than 1 per cent. Not enough information is available to classify wells according to base of oil or to make any statement relative to sands which cause these divergent qualities.

Very little is known concerning initial, closed pressures of wells because wells were never closed. Casing pressures as high as 1,000 pounds, with tubing pressures up to 400 pounds, have been recorded in wells flowing through a ½-inch bean. Fittings manufactured to resist 1,500 pounds of pressure have been broken by gas wells in the western area. Calculated hydrostatic pressure on sands at the *Scalez* horizon in the western area is 1,000 pounds, and in the eastern field, 1,375 pounds.

The temperature of oils when they reach the surface varies from 100° to 115° F. in flowing wells. In pumping wells, a lower temperature exists, probably because of loss of heat in the tubing. These temperatures are approximately normal for San Joaquin Valley fields.

DRILLING AND PRODUCTION METHODS

All wells are drilled with standard California rotary practice. No surface casing is required. A string of either 10-inch or 8¼-inch casing is cemented above the oil sand, and a 6¼-inch string, perforated through the oil sand, is run to the bottom. The tubing used is 3-inch, and wells are pumped on the walking-beam by individual steam engines. Considerable cleaning-out has been done with standard tools. Hot oil has also benefited some of the older wells when circulated into the oil sand.

PRODUCTION STATISTICS

Table I gives total oil, water, and shut-in production for the Elk Hills by years. The interesting fact is the rather constantly increasing water, which is encroaching on the east end of the eastern area and to some extent on the southeast end. The shut-in production of late 1922 and 1923 was economic and caused by the gusher fields of the Los Angeles Basin

bringing a flood of oil on the market. The shut-in figures for 1925 and 1926 were the result of operators' agreements, and the figures for 1927 and 1928 are increased because of wells closed by government orders on Naval Reserve lands.

Tables II and III show the range in production of some of the best wells and some of the poorest in both fields.

There are at present 328 producing oil wells, of which 26 are shut in. There are also 9 gas wells, 2 of which are practically shut in.

TABLE I

PRODUCTION IN ELK HILLS

(In Barrels)

Year	Total Oil Produced	Total Water Produced	Total Shut-in Production
1919	254,736	0	0
1920	6,074,103	6,294	0
1921	17,990,462	30,791	0
1922	11,604,314	134,085	3,091,481
1923	8,087,549	64,971	6,302,276
1924	13,530,234	557,212	343,030
1925	11,971,149	734,515	2,026,785
1926	12,292,754	1,036,134	3,900,900
1927	10,073,073	1,560,127	4,976,550
1928*	4,321,540	?	15,380†
Total, to June 30, 1928	96,199,914	...	...

* Figures obtainable only for first half of 1928.
† Daily.

Wells are spaced so as to allow 8 acres per well. Based on the production so far obtained in some of the best wells, recoveries up to 200,000 barrels per acre are indicated, but the average is only a fraction of this amount. Small wells, such as the Pan-American Petroleum Company's Greeley No. 1 in the western field, have an indicated ultimate recovery of approximately 65,000 barrels, or a little more than 8,000 barrels per acre. The total area actually producing is approximately 3,100 acres. From this area the total production up to June 30, 1928, was 96,200,000 barrels of oil, or approximately 31,000 barrels per acre. The present daily production is 22,000 barrels, and there are 15,380 barrels daily shut in. It would be justifiable, therefore, to estimate an ultimate recovery, based on these figures, of approximately 43,000 barrels per acre, or an ultimate for the 3,100 acres of 133,300,000 barrels, of which 96,200,000 has already been

produced, this being based upon no further drilling or deepening of old wells.

Without going into the controversy over the Elk Hills, the following statistics give an insight into the actual status of the Naval Reserve lands.

The first commercially productive well was completed on January 5, 1919, in the western field. On February 12, 1920, the first gusher well

TABLE II

PRODUCTION OF TYPICAL WELLS, WESTERN FIELD

	Standard Oil Company's Hay 1	Pacific Oil Company's Carman 3	Pan-American Petroleum Company's Greeley 1
Location*	36–30–23	36–30–23	36–30–23
Completed	Jan. 5, 1919	Jan. 30, 1920	Jan. 1 ,1920
I.P.†	230	1,800	530
Casing‡	....	....	8¼-inch, 2,335
Oil horizon§	....	....	2,655–2,900
Oil gravity	....	....	39.3° Bé.
Year:‖			
1919	106,927	....	....
1920	56,067	230,631	35,909
1921	28,329	50,443	5,339
1922	17,676	21,798	5,281
1923	12,611	12,199	3,372
1924	Data unavailable	Data unavailable	2,406
1925	Data unavailable	Data unavailable	1,806
1926	Shut in	17,080	1,781
1927	Shut in	15,540	1,491

* Section; township, south; range, east.

† Initial production in barrels.

‡ Depth, in feet, at which casing indicated was set.

§ Depth, in feet, of oil horizon.

‖ Production in barrels.

was completed in the eastern field. Up to September 30, 1921, 21,657,403 barrels of oil had been produced almost entirely by the Standard Oil Company of California, but none of this came from Naval Reserve land. On that day the first well on Naval Reserve land was completed with a production of 108 barrels per day. The government was slow in protecting its lands against drainage. Drilling on Naval Reserve land continued until receivers were appointed for the wells on March 17, 1924; and up to March 31, 1924, the total Elk Hills production amounted to 48,355,338 barrels, of which 8,679,681 barrels came from the Naval Reserve. As of June 30, 1928, the figures are 96,199,914 barrels from the Elk Hills, of which 31,705,478 barrels came from Naval Reserve lands. Table IV gives

the number of producing wells at present on the several classes of land. There are 69 producing wells on Naval Reserve land and 26 wells which

TABLE III

PRODUCTION OF TYPICAL WELLS, EASTERN FIELDS

	Standard Oil Company's Tupman 1	Pacific Oil Company's No. 22	Pan-American Petroleum Company's No. 1 G	Union Oil Company's No. 5
Location*	36–36–24	35–30–24	2–31–24	26–30–24
Completed	Feb. 12, 1920	July 26, 1920	May 23, 1922	Aug. 12, 1924
I.P.†	5,420	4,889	1,350	600
Casing‡	10-inch, 2,702	8¼-inch, 2,680	8¼-inch, 2,887	8¼-inch, 3,230
Horizon§	2,778–2,828	2,740–2,811	2,900–5,030	3,301–3,397
Gravity‖	25.4° Bé.	26.4° Bé.	24.8° Bé.	17.3° Bé.
Year:¶				
1920	1,563,918	530,524	....	....
1921	259,066	241,511	....	51,659
1922	145,583	91,835	232,450	145,644
1923	22,890 (shut in)	16,615 (partly shut in)	284,432	72,475
1924	Data unavailable	21,470** (partly shut in)	235,564	47,047
1925	Data unavailable	34,860**	203,665	18,768
1926	57,000**	36,870**	111,481	9,651
1927	52,482**	36,298**	14,788 (shut in March 24, 1927)	6,755

* Section; township, south; range, east.
† Initial production in barrels.
‡ Depth, in feet, at which casing indicated was set.
§ Depth, in feet, of oil horizon.
‖ Gravity of oil.
¶ Production in barrels.
** Estimated from daily averages.

TABLE IV

PRODUCING WELLS AND LAND CLASSIFICATION

	Private Land		U. S. Leased Land	Naval Reserve No. 1	
	Inside Limits of Naval Reserve No. 1	Outside Limits of Naval Reserve No. 1	Outside Limits of Naval Reserve No. 1	Producing	Shut in
Oil wells	42	140	51	69	26
Gas wells	7	....	....	....	2

are shut in. There are 233 producing wells on private land and government-leased land outside the Naval Reserve (Fig. 5).

The present daily production is approximately 22,000 barrels, of which 10,180 barrels comes from Naval Reserve land and 11,820 barrels from the remaining 233 wells. There is a shut-in production of 15,380 barrels, of which about half is on the Reserve.

PROBABLE ULTIMATE PRODUCTIVE AREA

An estimate of the area that will probably prove productive leads to the conclusion that the eastern field may include approximately 5,600 acres and the western field approximately 2,100 acres, a total of 7,700 acres. Of this area, 4,040 acres lie inside the Naval Reserve, or, stated in another way, 3,600 acres are privately owned or government owned, but outside the Reserve. The Hillcrest area, west of the western field, embraces a closed dome of unknown extent which has been tested in Sec. 28, T. 30 S., R. 23 E., to a depth of 1,661 feet, resulting in a gas well. There is probably oil to be found here, but estimates of the size of the productive area would be mere guesses at present. The minor folds on the south and west borders of the hills may furnish some production, and buttress sands may be discovered on the north flank.

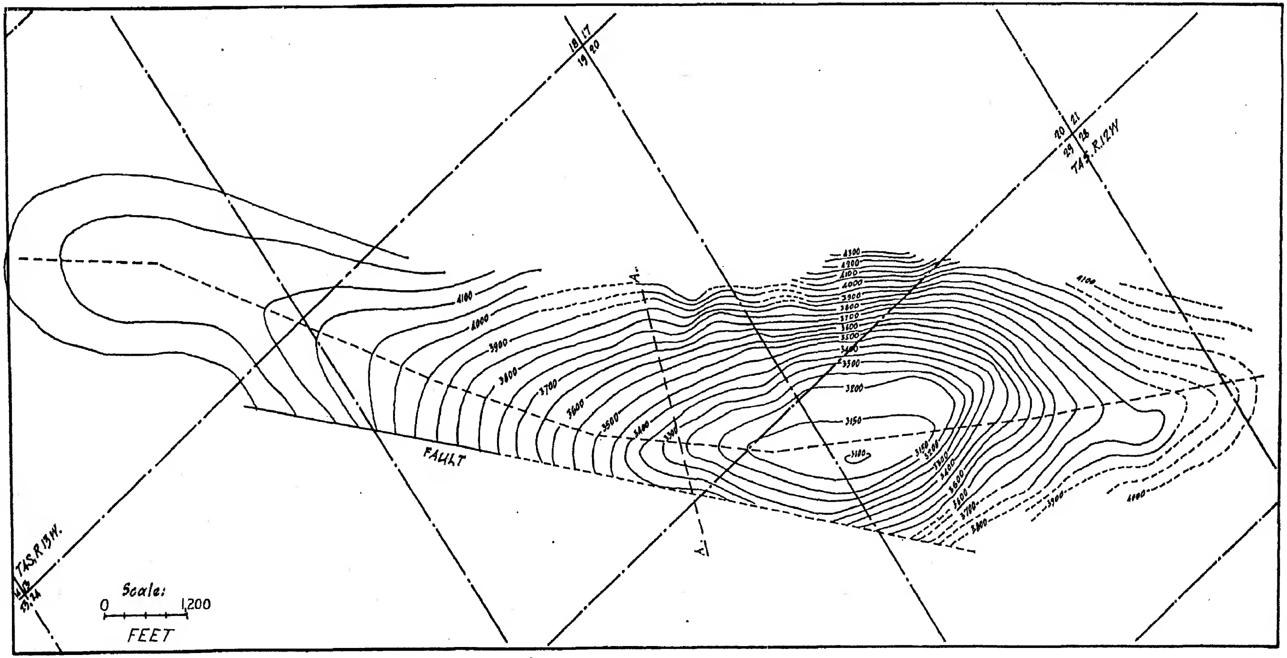

FIG. 1.—Subsurface structure of Long Beach oil field. Contours drawn on lower Brown zone. Figures give depth in feet below sea-level. Contour interval, 50 feet. Cross section *A-A* shown in Figure 2. This map modified from map of Long Beach oil field published in *Summary of Operations, California Oil Fields* (May, 1928).

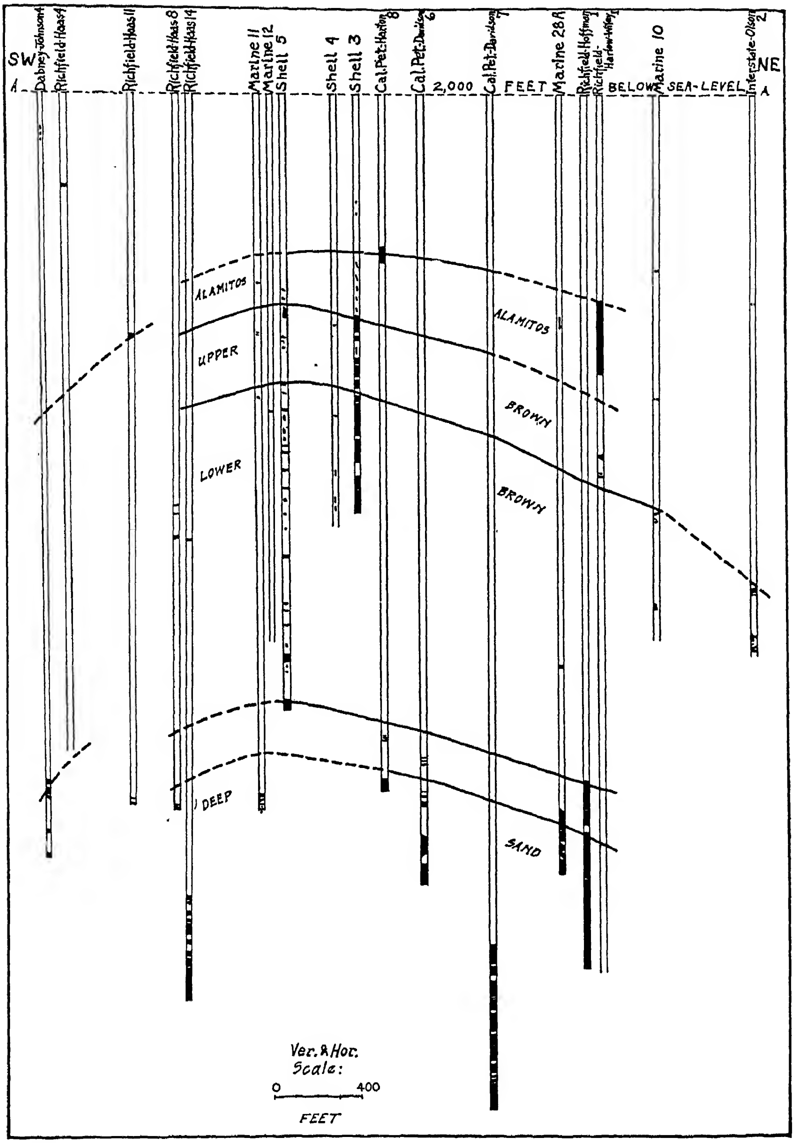

FIG. 2.—Cross section *A-A* (Fig. 1) southwest-northeast through Long Beach oil field. Modified from Plate V of Long Beach oil field in *Summary of Operations, California Oil Fields* (May, 1928).

HISTORY, 1921–23

The Long Beach field is in the northern limits of the city of Long Beach, approximately 2 miles from the Pacific Ocean, and in the southeastern part of Los Angeles County. It occupies a region of slight elevation, the highest point, Signal Hill, being 364 feet above sea-level. It has produced more oil than any other field in California.

On June 25, 1921, the Shell Company completed the first oil well, with an initial production of approximately 500 barrels of 22°-gravity oil. The location was made as a result of geological work by the Shell Oil Company. By the end of 1922, on account of town-lot drilling, the field was nearly 3 miles long and ½ mile wide. More than 2,500 feet of oil-bearing formations without any water had been developed in the center of the field, and the amount of perforated casing in most of the wells ranged from 1,000 to 2,000 feet. Three oil zones were recognized: the Wilbur, at a depth of approximately 2,300 feet, 200–250 feet thick; the Alamitos, 250 feet below the top of the Wilbur and 650–700 feet thick; and the Brown, 675 feet below the top of the Alamitos and 2,500 feet thick. The Brown zone was discovered in June, 1922, and proved to be more prolific than the higher zones.

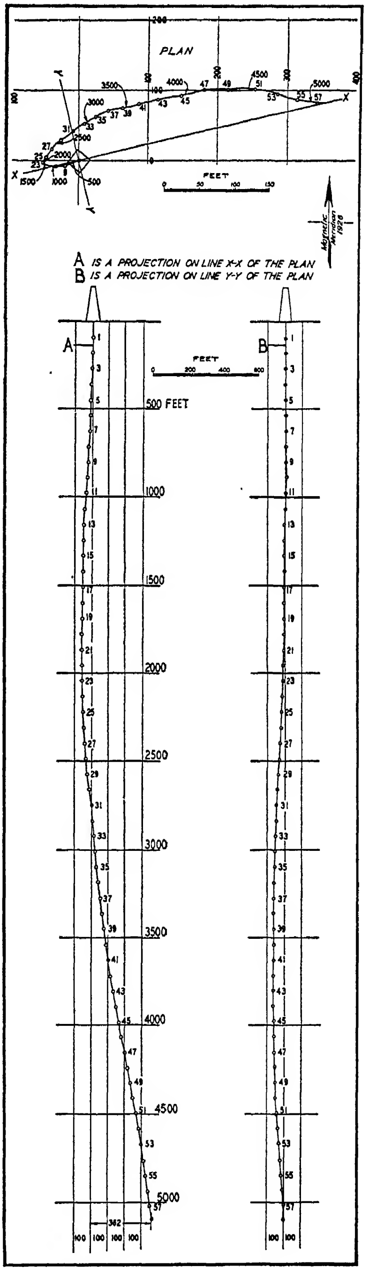

FIG. 3.—Survey of A. T. Jergins Trust's Well No. 15, Long Beach oil field.

The status of wells and production as of November 1, 1923, was as follows:

Daily average production, in barrels	225,000
Number of producing wells	272
Average daily production per well, in barrels	937
Total production to November 1, 1923, in barrels	72,000,000
Recovery per acre to November 1, 1923, in barrels	64,285

LATER HISTORY

During 1924 the proved area of the Long Beach field was extended slightly toward the northwest by several wells located west of American Avenue, which obtained production from the lower Brown zone. The field as a whole changed from a flowing to a pumping field, the proportion of pumping wells increasing from 30 to 70 per cent. The total production dropped from approximately 225,000 barrels per day to approximately 125,000 barrels per day, a decline of 40 per cent.

The intensive drilling of the Northwest extension or Los Cerritos area was the most important development in 1925. The proved area was extended north of Wardlow Road to Bixby Road, and west of American Avenue nearly to the tracks of the Pacific Electric Company. On December 31, 1925, 36 wells were producing north of Wardlow Road, the estimated total production for these wells being 9,000 barrels per day, or an average of 250 barrels per well.

In the early part of 1925, there was some activity in the old part of the field whereby water troubles in many wells were corrected by re-drilling and plugging. As a result the production of this part of the field was kept fairly constant. With the increase of excitement over the Los Cerritos district, work in the old part of the field came to a standstill. The total production of the field December 31, 1925, was 108,986 barrels per day, averaging 175 barrels per well.

During 1926 the drilling activities in the Northwest extension reached a peak, and the limits of this area were definitely established as being Roosevelt Avenue on the north and Lincoln Avenue on the west. The peak of production for this area was reached in the middle of July, 1926, when 18,337 barrels of oil per day was produced, an average daily production of 122 barrels per well.

Considerable interest was aroused after the Carson Oil Corporation, in November, 1926, perforated the water string in Well No. 13, located southeast of the intersection of Brandon Street and Atlantic Avenue in the Northwest district. The $8\frac{1}{4}$-inch casing was perforated from 3,220 feet

to 3,300 feet, approximately 200 feet above the shut-off depth; and the well came in at the rate of 500 barrels per day.

The possibilities of deeper production stimulated some deep drilling in the Lovelady district. The Richfield Oil Company of California drilled Hass No. 8, located southeast of the intersection of Willow Street and Orange Avenue, to a depth of 5,317 feet and obtained 2,000 barrels of oil per day. The Pan-American Petroleum Company drilled Chainey No. 2, located a little west of Hass No. 8, to a depth of 5,389 feet and plugged to 5,262 feet, obtaining an initial production of 1,200 barrels. Several wells south of Grant Street and west of Enos Street were deepened with favorable results. The total production of the Long Beach field December 31, 1926, was 92,961 barrels per day, a daily average of 133 barrels per well.

The early part of 1927 was characterized by little activity in the Long Beach field other than the abandonment of many wells in the Los Cerritos district and some shallow drilling along the southwest edge of the field. The deep-drilling campaign started intensively in October, 1927, several wells having been completed in the deep sand earlier in the year. Two of the most important of these were the Graham-Loftus Oil Company's Leightburn No. 3, located just south of the cemetery on Willow Street, and the Pan-American Petroleum Company's Pyle-Coffin No. 1, located on Summit Street east of Obispo Avenue. These two wells proved the existence of the deep sand in an area which extended about 1½ miles along the structure. The Graham-Loftus Oil Company's Butler No. 1 was completed in the deep sand December 5, 1927, extending the proved area of deep sand northwest of the cemetery.

At the beginning of 1928, many wells were drilling with the deep sand as the objective. The outpost deep-sand well on the western end of the field as of April 30, 1928, is Keck Syndicate No. 5, Well No. 3, located on Elm Avenue south of Thirty-first Street. Several wells have been drilled into the deep sand west of Atlantic Avenue, but none of them except Keck Syndicate No. 5, Well No. 3, are as yet commercial producers because of water which was located at approximately 5,630 feet in the Rainbow Petroleum Company's Dutcher No. 1. At the southeast end of the field, the Herndon Petroleum Corporation's Herndon No. 4 is the outpost commercial producer at this time. No wells have been drilled into the deep sand east of this location.

At this time 73 wells have been completed in the deep sand. The average daily production per well is 1,315 barrels of oil (Fig. 4); 196 wells are still drilling.

LOWER BROWN ZONE CONTOUR MAP

The lower Brown zone contour map (Fig. 1), compiled by several members of this department, was finally drawn up and completed by F. A. Graser. The basis for the contours is a shale body above the lower Brown oil sands, which seems to extend throughout the field. The shale bed varies in thickness in short distances and is not found in the log of every well, but it is so consistently conspicuous in the logs of most wells that its absence in a few can be disregarded. Much of the information from which this map was prepared was derived from a study of a peg model and numerous cross sections. An area southwest of the fault zone has not yet been contoured, but it is hoped that the information obtained from the new wells now drilling will make it possible to complete the contouring of the sands underlying this area.

As a result of the work done in preparing this map, it was found that what has been known as the "Wilbur" sand is the upper part of the Alamitos sands, and is so considered in this report. The Alamitos zone is approximately 650 feet thick at the top of the structure, and its sands gradually lense out, the upper sands having the smallest areal extent.

FAULT ZONE

The existence of a fault extending northwest and southeast was indicated by the results obtained in drilling for upper Alamitos zone production in the vicinity of Thirty-first Street and Pasadena Avenue. The top of the productive horizon was located at 3,228 feet in the Stevens Drilling Company's Poppy No. 1, and the sand became known as the Poppy sand. Several wells were drilled along a northwest-southeast line approximately 100 feet northeast of Poppy No. 1, but none of these wells encountered the Poppy sand, indicating that they were drilling where different conditions exist. The wells which failed to find the Poppy sand at this location are the Petroleum Company's Well No. 2, the Stevens Drilling Company's Steve No. 2, and J. E. O'Donnell's O'Donnell No. 59.

The core samples from practically all of the deep wells drilled along this line were found broken, and in some wells completely crushed, indicating a fracture zone along this line and in its near vicinity. Of course the core sample may reflect only a local condition and may not be reliable as a basis for determining structure; but where the formations, cored at approximately the same depth in several wells along a general line, are found shattered, this may be interpreted to indicate a fault zone.

Several wells drilled on the south side of the field failed to encounter any of the deep-sand production, finding only gray sands. The deep-

sand formations dip very steeply on this side of the field, some of the core samples showing dips as great as 80°. These wells which failed to find the deep sand probably drifted down-dip, thus failing to penetrate

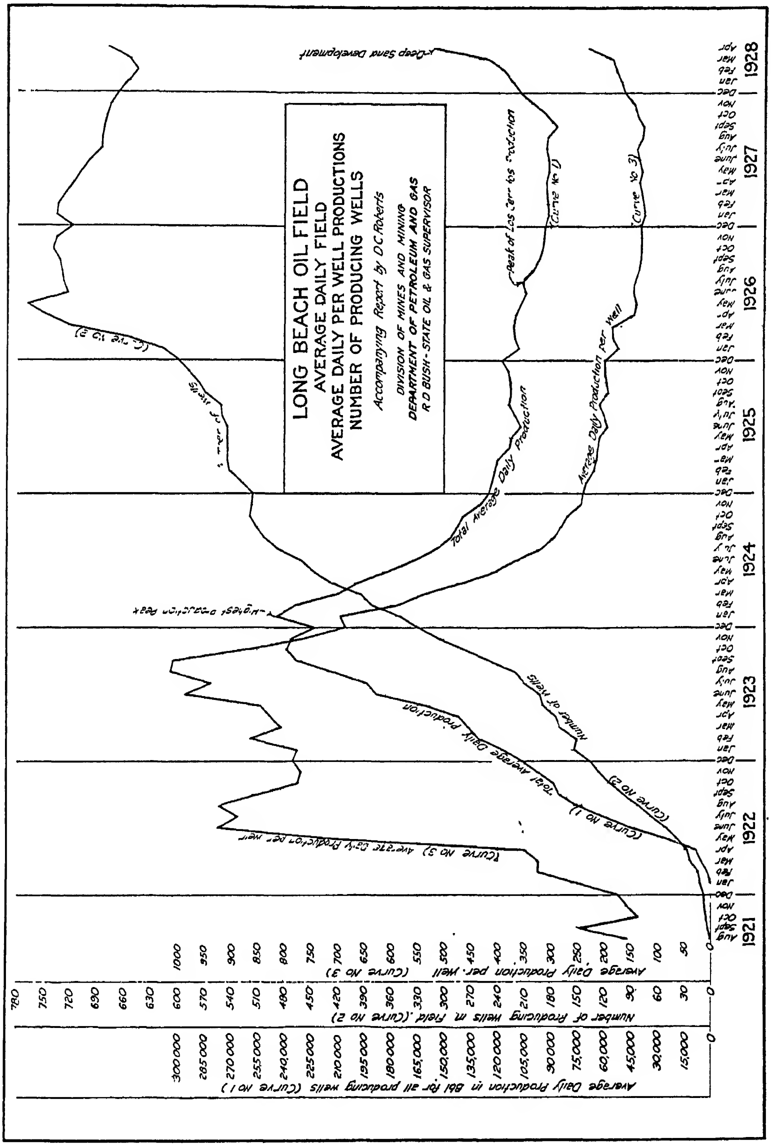

FIG. 4.—Curves showing average daily production of Long Beach oil field.

the oil-bearing sands; or they may have been cut off by the fault. These wells are located in practically a straight line. Five wells, drilled south of this line, encountered the deep sand; these wells are the McKeon Drilling Company's Thorne No. 1, the Dabney-Johnston Oil Corporation's Well No. 4, the State Company's Well No. 1, George F. Getty's Well No. 18, and the Shell Company of California's Cherry Hill Community No. 5. Of these, only the Dabney-Johnston Oil Corporation's Well No. 4 is completed to date. It is open to a zone from 5,146 to 5,515 feet and is now producing 873 barrels of oil per day, cutting 12 per cent emulsion. That these wells are encountering oil sand at these locations may be attributed to the fact that they are crooked holes, their bottoms being north of this line. It would be very interesting to know what a survey of these holes would show.

MIOCENE CONTACT

The exposed formations are of lower San Pedro age. Their thickness ranges from 1,000 to 1,300 feet. They are unconformably underlain by the Fernando formation of Pliocene age, which contains the oil and gas zones.

Miocene micro-fossils have been found in several wells according to some paleontologists. Geologists and paleontologists for the largest operator in the field can find no definite Miocene markers in the formation samples that they have investigated.

According to those who believe they have located the Miocene horizon, an intermediate zone, approximately 400 feet in thickness, composed of seemingly re-worked material, lies between the lower Pico and the top of the true Miocene. The following is a résumé of the investigation of the core samples taken from several wells:

Richfield Oil Company of California's Hass No. 14:

5,700–5,823 feet: sponge spicules, fish remains, and fragments of pectens—intermediate zone

5,823–5,952 feet: shale pebbles and samples of diatoms indicating Miocene

Richfield Oil Company of California's Kelly No. 1:

5,474–5,729 feet: lower Pico *Foraminifera* at 5,474 feet; no definite fossils between 5,474 feet and 5,729 feet—intermediate zone

5,729–5,756 feet: Miocene *Foraminifera*

Pan-American Petroleum Company's Chainey No. 2:

5,390–6,160 feet: lower Pico *Foraminifera* common throughout. Notice that this well is located only 100 feet southeast of Kelly No. 1

Richfield Oil Company of California's Hoffman No. 1:

Only sample, 5,252 feet: lower Pico fauna

Superior Oil Company's Crew 2-A:

5,594–5,802 feet: typical intermediate-zone fossils

5,802–6,107 feet: Miocene fossils

Richfield Oil Company of California's Booth No. 8:

Sample from 5,862 feet contained a few Miocene fossils

George F. Getty's Well No. 6:

5,103–5,842 feet: lower Pico fossils

5,842–5,962 feet: intermediate zone; no Miocene fossils found

Exactly what is the productivity of this lower, possibly Miocene, sand cannot be stated, as there are not sufficient data available to make a satisfactory comparison of the production obtained from wells producing from only lower Pico and those producing from both lower Pico and Miocene together. No well is producing exclusively from this lower, possibly Miocene, sand at this time.

CROOKED HOLES

Several wells have been surveyed by Alexander Anderson,[1] whose apparatus and methods of surveying wells are accepted generally as accurately showing the drift of bore holes. These surveys have shown that most of the wells surveyed are very crooked, some having drifted more than 1,000 feet from the vertical. They also indicate that the tendency is to drift toward the axis of the structure rather than down dip. Some of the holes were found to be spiral.

A copy of Anderson's survey of the A. T. Jergins Trust's Well No. 15 is presented (Fig. 3) to show how these crooked holes make it difficult to correlate by ordinary methods. The only way a crooked hole can be correlated accurately is by first making a survey to determine the drift of the hole and then applying proper corrections for this drift.

By referring to the survey of the A. T. Jergins Trust's Well No. 15, it is noticed that the vertical distance from the derrick floor to the bottom of the hole is actually 5,096 feet instead of 5,132 feet as measured by the drill pipe. Also, the hole drifted 360 feet, mostly in a northeasterly direction, or up-dip, when the reported depth was 5,132 feet. In other words, the bottom of the hole is actually approximately 90 feet higher on the structure than it appeared to be before making the survey. This is considered to be a fairly straight hole in comparison with most of those surveyed.

During the deep-drilling campaign many unexplainable inconsistencies have been encountered, such as the problem of two wells located in

[1] Mining and petroleum engineer, Fullerton, California.

the Hill district, across the street from each other. At the same drill-pipe depths one of these wells cored a formation with a very steep dip, while the other cored what appeared to be the same formation with practically horizontal bedding planes. This difference may reflect simply a local condition, having no bearing on the general structure, or it may be due to crooked holes. Neither of these holes has been surveyed.

RELATION OF PETROLEUM ACCUMULATION TO STRUCTURE

The structure of the Long Beach field is that of an asymmetric anticline the axis of which trends southeast and northwest. In the northwest end of the field the axis curves toward the north, where the structure flattens into a terrace. A fault truncates the southwest side of the structure, with an uplift on this side of approximately 350 feet.

The production obtained from wells on the south side of this fault seems to be more prolific and stable than that obtained from wells on the main structure. It may be that this is due to the fact that the beds dip more steeply on the south side and that a greater amount of the sand is actually exposed to production in the wells drilled in this locality, or it is quite possible that the oil has been trapped in the sands because of the displacement of the formations there.

The wells drilled in the center of the anticline ordinarily have large initial production, but they seem to decline with great rapidity, partly because 1,000–2,000 feet of formation is usually left open, thus exposing the oil to "thief sands" which absorb it. Some of the wells drilled on the very top of the anticline have failed to show an initial production of more than 300 barrels per day, although drilled in accordance with the same program as wells in the same area which had initial productions of more than 2,000 barrels a day. Such inconsistencies are very difficult to explain, and though many engineers have puzzled over this question, no satisfactory explanation can yet be offered.

Cores of the formations on the axis of the structure show the beds to be broken and fractured and to vary from horizontal in one well to vertical in the adjoining well, indicating that there has been great stress exerted during the folding of the beds. This fracturing may have opened the sands so as to allow the oil to migrate into barren sands, which resulted in the depletion of the oil-bearing sands. Another explanation of some of the inconsistencies in the production obtained from wells drilled on top of the structure may be the facts that in the early days of the development of the field many wells were drilled to a depth of more than 5,000 feet in this area and that there was little or no attempt made to maintain a

proper gas-oil ratio in flowing wells. This resulted in a loss of energy which might have been utilized to obtain a much greater ultimate recovery.

On the north side of the structure the beds have a more gentle dip, and water troubles are much more inherent in the deep sand. The Richfield Oil Company of California's Hoffman No. 1 is the only well that has produced consistently from the deep sand in this part of the field, and many offer the "crooked-hole" explanation for this.

The deep sands on the northwest end of the structure have not yet been prospected. It is possible, if the sands are productive there, that they will be found to be thin and not highly productive, as is the condition in the Brown zone sands, in that part of the field.

The southeastern part of the structure plunges off steeply. The production obtained there from the deep sand is very large in wells near the axis, but is very small in the extreme southeastern part of the field where the average daily production varies from 200 to 300 barrels.

CONCLUSION

The peak of the deep-sand drilling campaign should be reached during the latter part of May, 1928. One hundred and ninety-six wells are now drilling to the deep sand, and most of them have cemented the top-water strings and are down at least to the Brown zone horizon.

It is estimated that the production will reach a peak of nearly 200,000 barrels per day during June, when most of the present drilling deep wells will have been completed. This prediction is based upon the present average daily production of 96,000 barrels from 73 deep wells, equivalent to 1,315 barrels per well per day. The consistency with which big producers continue to come in, and the great thickness of nearly virgin formations available to sustain production from immediate marked decline regardless of the number of completions, are considered sufficient justification for the prediction of a 200,000-barrel peak.

The possibilities of finding the deep zone in the Los Cerritos district have not led any of the operators to drill for it as yet. This zone probably exists, but whether it thins out, as the lower Brown sands do, is a question that can be answered only after a well is drilled through it. It would probably be necessary to drill to a depth of approximately 6,000 feet in order to encounter the deep-zone horizon, and the memories of the Los Cerritos disaster in the Brown zone are still fresh in the minds of the operators. They are waiting until the drilling of the Northwest district has proved the existence of the deep sands in the vicinity of Wardlow

Road and American Avenue before risking money in drilling a deep well in the Los Cerritos area.

In the Southeastern district, the Herndon Petroleum Corporation's Herndon No. 4 located the top of producing sands at 5,420 feet, and this indicates that there is a very good chance that the deep sand may be found to extend some distance southeast of this location, and the field may be extended somewhat in that direction.

At this time the deepest producing well in the field is the Shell Company of California's Martin No. 4, producing from depths ranging from 5,263 to 7,060 feet. The Richfield Oil Company of California's Denni No. 6 is being completed at a depth of 7,401 feet. No well has yet been drilled to a depth below which there is no possibility of finding additional oil-bearing formations. The ultimate vertical footage that can possibly be obtained cannot be estimated from any available data. Predictions of 10,000-foot wells are only conjectures on the mechanical feasibility of getting a well on production at that depth. Although a depth of 10,000 feet does not seem mechanically feasible at this time, improvements in machinery and methods during the next few years may make much greater depths attainable than are now possible. In 1921 a depth of 7,000 feet was not considered feasible. There is great danger in drilling to these great depths even on top of the structure, if the formations are not cored continuously, as several operators can testify. Even when cored, the well may produce water, as not all cores show the presence of water, especially where it occurs in a lean oil sand.

The Long Beach field produced 258,606,450 barrels of oil from June, 1921, when it was discovered, to December 31, 1927, from 1,350 acres, equivalent to a recovery of 191,560 barrels per acre. These figures include little production from the deep zone as most of the deep-zone wells were completed after January 1, 1928.

SURFACE STRUCTURE, FLORENCE OIL FIELD, FREMONT COUNTY, COLORADO[1]

RONALD K. DE FORD[2]
Roswell, New Mexico

ABSTRACT

The Florence field occupies a strip 3 miles wide on the eastern limb of a geosyncline. The oil occurs in fissures in the Pierre shale. The general dip throughout the field ranges from 2° to 5° westward. The eastern boundary of the field is a steep monocline that brings the productive beds to the surface. The western boundary coincides approximately with the occurrence of a heavy sandstone overlying the Pierre shale. Possibly the removal of the sandstone allowed the fissures to open and the oil to accumulate. Thus the accumulation may be as recent as present topography.

INTRODUCTION

The Florence oil field, in Fremont County, south-central Colorado, is named after the town of Florence, which stands on the south bank of Arkansas River 10 miles below Cañon City (Fig. 1). Two miles west of Cañon City the river emerges from the Royal Gorge, a deep and narrow breach in the eastern granite rampart of the Rocky Mountains, and flows east across the upturned edges of sedimentary formations dipping steeply eastward. Not far below Cañon City the dip reverses and the beds dip gently toward the west, forming a syncline. The Florence field occupies a part of the eastern limb of this syncline, extending from the town of Florence southward 8 miles.

The structure of the surface beds was mapped in 1925 with the assistance of Louis W. Cramer. No study of well logs has been made; nor is it thought that such a study would be justified, because of the lack of traceable markers in the Pierre shale. A brief description of subsurface occurrence of oil is taken from Washburne.[3]

Mapping of the west side of the field was on members of the Trinidad sandstone; of the east side on thin, reddish, limonitic, concretionary beds

[1] Presented by title before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, July 24, 1928. Published by permission of The Midwest Refining Company, Denver, Colorado.

[2] Geologist, The Midwest Refining Company.

[3] See bibliography at the end of this article, 1910, first item.

in the Pierre shale. Most of these markers in the Pierre are a few inches thick and only a few hundred feet in length along the outcrop. The

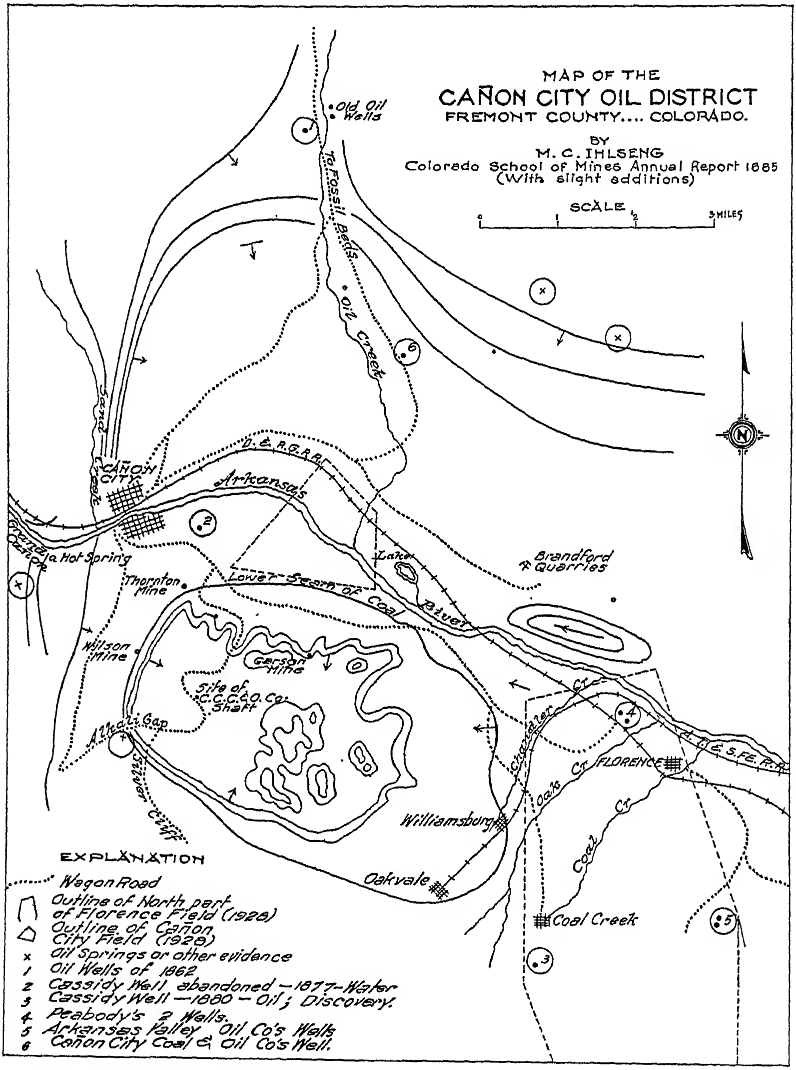

FIG. 1.—Historical map of Cañon City oil district. Mapped by M. C. Ihlseng.

Cañon City field had not been discovered, and its area was not mapped.

HISTORY

The oil-producing district in the vicinity of Cañon City and Florence is one of the oldest in the United States. The first wells were sunk near a seep on the bank of Oil Creek 9 miles northwest of the town of Florence and 6 miles northeast of Cañon City. The early history is told in the charming language of M. C. Ihlseng:[1]

> A. M. Cassidy, of Denver, ... was directed to the region through reading a book of travels by one of the early explorers—a captain in the regular service—who noted indications of oil in the district now called Oil Creek, about six miles northeast of Cañon City. Here operations were commenced by Cassidy in March, 1862. He sank six wells on Oil Creek to a depth of from 60 to 90 feet, and two as far down as 400 feet, but found oil only in the strata near the surface. This was pumped and crudely refined by improvised machinery, ... and shipped to the Denver and other markets in the Territory, where it sold readily at from $1.25 to $2.85 per gallon, ranging in 1864, during the disturbance of trade by Indian incursions, as high as $5.00 per gallon. Up to 1870, when the railroad and the Continental Oil Company appeared in the market, the sales of crude Cañon oil amounted to an approximate total of three thousand gallons.

Cassidy induced others to help him drill deeper wells on the south, locating the first well in the valley of the Arkansas near Cañon City. The second test near the town of Coal Creek found oil in 1880. It was the first well of the Florence field, although it did not produce, and was abandoned because of lost tools. In the following years more wells were drilled by companies locally organized. Development has continued to the present.

STRATIGRAPHY

Table I gives a list of beds exposed in the vicinity of Florence and Cañon City from the youngest at the top to the oldest, with approximate intervals.

In a section a short distance north of Cañon City the granite is overlain by approximately 300 feet of pre-Pennsylvanian marine sandstone and marine limestones, overlain, in turn, by 1,400 feet of Red-beds that are arkosic except near the base, where they contain thick conglomerate beds of limestone boulders. These Red-beds correspond with a part of the Fountain formation of the Colorado Springs area, where at least the basal part is Pennsylvanian and the topmost part not younger than Permian.

Sandstone, approximately 100 feet thick, rests on the Red-beds near Cañon City and grades eastward into sandy gypsum beds of similar

[1] See bibliography at the end, 1885.

thickness. The gypsiferous beds underlie the Morrison formation and, judged from well samples,[1] grade upward into the Morrison. The gypsum

TABLE I

BEDS EXPOSED NEAR FLORENCE AND CAÑON CITY, COLORADO

System	Group	Description	Thickness in Feet
Recent		Soil and alluvium Terrace gravels	
Eocene		Remnant of volcanic tuff Coarse conglomerate	500
—*Unconformity*—			
Cretaceous	Montana	Vermejo formation: sandstone, shale, coal Trinidad sandstone Pierre shale, gray	1,000± 150–200 3,500
	Colorado	Niobrara formation: Apishapa shale, calcareous, light gray to buff Timpas limestone Benton formation: Carlile sandstone Carlile shale, black Greenhorn limestone Graneros shale, gray	 600 115 5 180 40 240
	"Dakota"	Dakota sandstone, soft and white Purgatoire shale and sandstone	100 240
—*Disconformity*—			
Jurassic(?)		Morrison formation: sandstones and vari-colored shales Todilto(?) formation: arkosic conglomerate at Cañon City (changing to gypsum eastward)	310* 110*
—*Angular unconformity*—			
Permian(?) and Pennsylvanian		Red-beds (arkosic)	1400*
—*Unconformity*—			
Mississippian		Millsap limestone	0–50*
—*Unconformity*—			
Ordovician		Fremont limestone Harding sandstone	120* 125*
—*Unconformity*—			
Pre-Cambrian Crystallines			

* At the place measured: north of Cañon City, Sec. 30, T. 18 S., R. 70 W., and Sec. 25, T. 18 S., R. 71 W.

beneath the Morrison is widespread in southeastern Colorado and northeastern New Mexico, although it is not everywhere present. In many

[1] Samples from the Phillips Petroleum Company's Niles No. 1, Sec. 27, T. 16 S., R. 65 W., El Paso County, Colorado. The unconformity overlain by the gypsum is recognizable in these samples.

places it lies upon the Wingate (or Exter) sandstone, and in a few places directly upon an unconformable surface of the Red-beds. Its probable equivalent is Darton's gypsiferous Todilto formation of central New Mexico.

The Todilto(?) sandstone near Cañon City contains large angular fragments of pre-Cambrian rocks, and the Red-bed surface it rests upon is an unconformable one. This is illustrated a few miles south of Cañon City, on Grape Creek, where the sandstone rests upon successively older members of the more intensely folded Red-beds, finally resting directly upon the granite. In Webster Park, farther west and across the first mountain, the sandstone is missing, and the Morrison formation is in contact with the granite. The same unconformity is probably that marked by the Shinarump conglomerate of Utah and Arizona.[1] It records a time of great diastrophism widespread in the Rocky Mountain region—the greatest diastrophism between the early Pennsylvanian (or possibly some period still more remote) and the end of the Cretaceous.

Whether this unconformity has any connection with the oil seeps in the Morrison formation and whether the oil seeps are related to the oil in the Pierre shale at Florence cannot be determined. Anyone who affirms that the oil is not indigenous to the Pierre shale, but comes from a lower source, might here find useful material for an alternative theory.

The Morrison formation is approximately 300 feet thick and consists of varicolored shales, sandstones, and a few thin limestones. It is generally referred to as the unmistakable type formation of fresh-water continental origin. It has been a prolific source of dinosaur bones throughout the Rocky Mountain region. The Oil Creek seep 6 miles northeast of Cañon City comes from the Morrison formation. Washburne[2] mentions other occurrences of oil in the Morrison in the vicinity of Florence and Cañon City. All these oils are heavy, black, and viscous.

The "Dakota group" is mainly sandstone containing here only thin beds of black shale in the middle part. "Solid black bitumen was found in it near Cañon City,"[3] and many seeps issue from it at different places in the Rocky Mountain region. It produces oil in Wyoming, northwestern Colorado, and northwestern New Mexico.

The Colorado group of Cretaceous beds above the Dakota sandstone does not require detailed description. The Carlile sandstone is not

[1] According to R. C. Coffin, the Shinarump is the horizon of greatest unconformity in the Utah-Arizona country. Personal communication.

[2] *Op. cit.* (1910), p. 520.

[3] *Ibid.*, p. 520.

porous enough to permit artesian flow of water, but it has yielded salt water and slight showings of oil in some wells. The Timpas limestone is an important bed in connection with both oil migration and with structure: its 100 feet of limestone should serve as a cap rock impervious to upward migration; mechanically it is competent to withstand strains and to transmit stresses. Above it is the calcareous Apishapa shale. "Fish scales are abundant in the Apishapa, and both formations everywhere contain much solid bitumen scattered through the pores and smaller joints, but none in the larger fissures."[1]

Overlying the Colorado group is the Pierre formation, which yields the oil at Florence. Throughout this almost uniform body of gray shale occur thin reddish limonitic concretionary beds that were of great use in mapping. A 1,000-foot zone of the Pierre shale, approximately 2,400 feet above the Carlile sandstone, contains the remarkable Teepee Buttes, which are cylindrical shell reefs of considerable vertical extent, comprised chiefly of *Lucina occidentalis* embedded in a calcareous matrix. Where exposed by erosion, they form small prominent buttes that stand like large Indian teepees above the level outcrop of the Pierre. In the teepee butte zone and above it are similar but smaller aggregates that might be called incipient teepee buttes. These masses, large and small, may be the cause of some of the crooked holes reported in the Florence field. The upper part of the Pierre formation contains thin sands which increase in number toward the base of the Trinidad sandstone.

The massive Trinidad sandstone, which lies upon the Pierre formation, is much the same in thickness and appearance in its entire outcrop west of the Florence field. Detailed mapping proved, however, that it mounts upward through the section in extending northward. Basal members of the massive Trinidad at the south end of the area interfinger with shale, becoming farther north the thin sandstones of the upper Pierre; thin sandstones and interbedded shales above the massive Trinidad grade into sandstone without shale and become part of the massive Trinidad. The Trinidad sandstone at the north end of the Florence field is several hundred feet higher, stratigraphically, than at the south.

The marine Trinidad sandstone is overlain by the coal-bearing part of the Vermejo formation. The upper Vermejo sandstones, barren of coal, form the rim rock of a steep escarpment west of the Florence field, where the total thickness of Vermejo and Trinidad, overlying the Pierre shale, exceeds 1,000 feet.

[1] *Ibid.*, p. 519.

OCCURRENCE OF OIL

Washburne found that oil occurs in joints and fissures in the Pierre shale.

The evidence consists (*a*) of observations on the correspondence in direction of the major joints observable in the rocks at the surface with the alignment of wells which have interfered with each other; (*b*) of the fact that many wells have been drilled within a few feet of each other without encountering oil at the same depth; (*c*) of the fact that gas struck in a shallow well often immediately ruins an adjacent well several hundred feet deeper by tapping the source of pressure; (*d*) of the fact that many wells drain adjacent wells that are very much shallower; (*e*) of the indications of vertical connection between the oil bodies shown by the marked increase in maximum pressure with depth; and (*f*) of the dissimilar pressures in adjacent wells of the same depth.

TABLE II

YEARLY PRODUCTION OF TWO WELLS, FLORENCE FIELD, IN BARRELS

Year	Well No. 85	Well No. 86	Year	Well No. 85	Well No. 86
1895	1,600	900	1912	170	3,000
1896	14,000	22,600	1913	450	2,900
1897	9,800	19,100	1914	290	2,800
1898	8,300	13,600	1915	230	2,300
1899	5,800	11,200	1916	230	2,400
1900	4,200	9,800	1917	190	2,500
1901	3,100	8,300	1918	180	2,300
1902	2,500	7,600	1919	160	2,100
1903	2,000	7,000	1920	150	4,500
1904	1,400	6,100	1921	220	5,000
1905	1,100	5,000	1922	117	7,000
1906	1,000	4,600	1923	158	6,500
1907	740	4,100	1924	215	7,100
1908	760	3,700	1925	140	7,900
1909	620	3,400	1926	88	7,200
1910	480	3,000	1927	15	5,800
1911	450	3,000			

To account for the body of oil disseminated through the Pierre shale and feeding the fissures, one naturally seeks the help of the irregularities—the "breaks"—in the otherwise dense body of gray shale. It may be that the sandy zones, thin sand beds, numerous concretionary beds, possibly even the buried Teepee Buttes, are reservoirs for this disseminated supply.

As a rule the wells are long lived. For example, Wells No. 85 and No. 86 began producing in 1895 and were still producing in 1927. The approximate figures on these two wells are given in Table II through the courtesy

of the Continental Oil Company. The decline during the first few years of the life of a well follows closely what Herold[1] calls "capillary control," but in the later years production holds up remarkably. The decline is so slow that other factors cause fluctuations of the curve, actual increases in production during some years, instead of a steady decline. One well in the field produced more than 600,000 barrels. The wells finally become exhausted but do not go to water.

RELATION OF ACCUMULATION TO STRUCTURE

The field is on the east flank of a somewhat complicated synclinal basin that lies between two major anticlinal folds, the Wet Mountains on the west and the southward prolongation of the axis of the Front Range on the east (Figs. 2 and 3). This basin is called the Cañon City embayment because it is a sedimentary indenture in the eastern side of the granite Rockies. Its sediments are bounded on the west, north, and northeast by the crystalline rocks of the pre-Cambrian; that is, by "granite." Garden Park, the northern head of the syncline, is a narrow sedimentary trough west of the Pike's Peak mass. The syncline plunges southward and widens, its main axis passing immediately east of Cañon City and 6 or 7 miles west of Florence. On account of the steep folding on the western margin of the embayment, the synclinal axis lies only 3 miles east of the granite outcrop. Not many miles south of Cañon City the syncline reaches its deepest point, and rises again southward, forming the basin, with the youngest coal-bearing formation in the middle and the outcrops of older formations circling successively around it. The steep folding on the western margin of the embayment changes southward to an overthrust of the granite onto Cretaceous beds, against which faulting the main synclinal axis terminates.

From the deepest part of the Cañon City embayment the beds rise eastward for approximately 25 miles to the Front Range axis. In round numbers the total rise is 5,000 or 6,000 feet, giving by calculation an average eastward rise (or westward dip) of 2° or a little more. However, the details are far from this simple average, as shown in the somewhat generalized sketch (Fig. 3).

A remarkable, steep monocline bounds the Florence oil field from north to south at its eastern edge. In places the dips are as great as 45°

[1] Stanley C. Herold, "Jamin Action—What It Is and How It Affects Production of Oil and Gas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 6 (June, 1928), pp. 659–70; also *Analytical Principles of the Production of Oil, Gas, and Water from Wells* (Stanford University Press, 1928).

westward. The monocline is 1½ miles wide and brings Niobrara limestones to the surface. Approximately 3 miles north of Florence it turns sharply westward as shown in Plate 1.

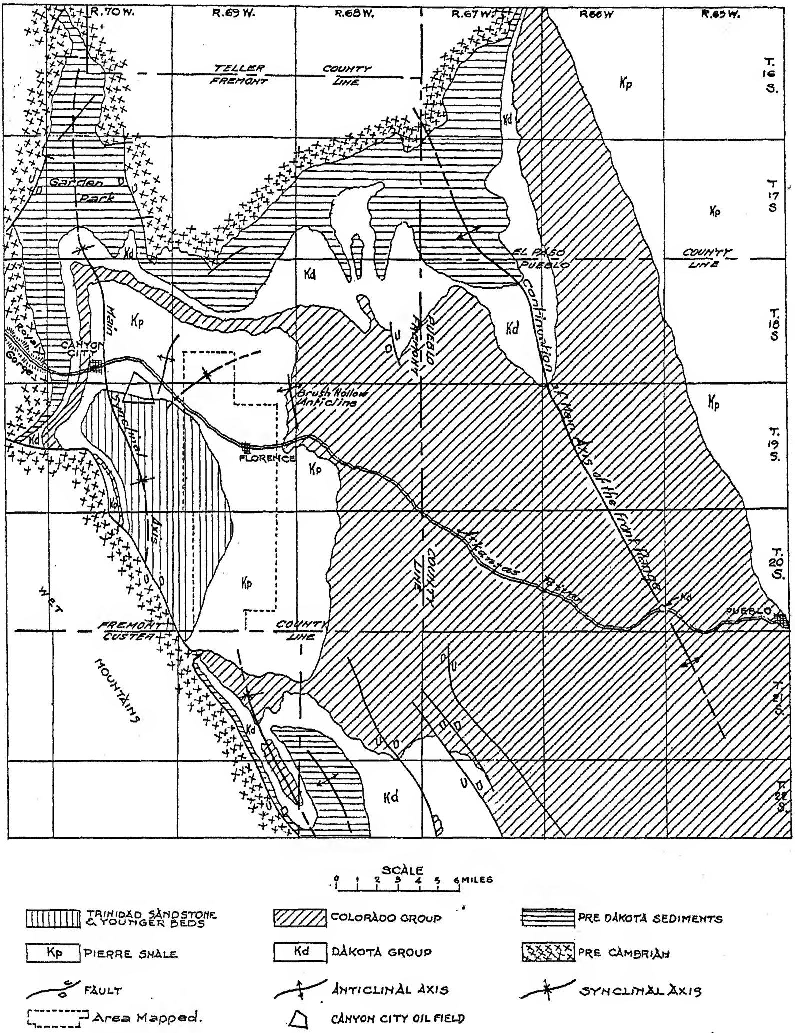

FIG. 2.—Regional structure in south-central Colorado.

Directly east of Florence the dips in the monocline are among the steepest, and faults occur. Possibly Washburne is correct in writing that

no oil is found here because the steep dips and faulting have permitted water circulation that has dissipated the oil; possibly the oil itself has escaped along the steep bedding planes and through the faults. Whatever the cause, practically no oil has been found farther east of Florence than

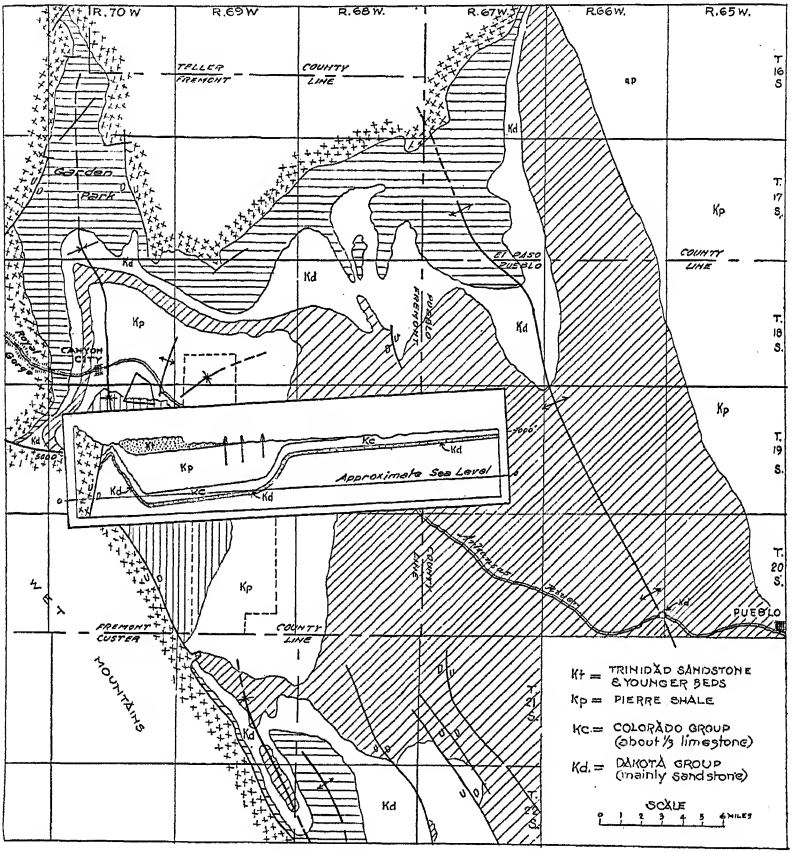

FIG. 3.—Generalized structure section through Florence field.

the eastern boundary of 5° dips. This line is shown on the structure map (Plate 1). All along it the beds rise eastward at approximately 5°, and immediately east of it the rise increases rapidly to make the steep monocline described. A similar line, the "eastern boundary of 8° dips," also appears on the map a short distance east of the 5° line.

In the more newly discovered, southern part of the field, the mono-

cline is less steep, and faulting in it is rare. The maximum dip measured is 17°. Here the oil shows little regard for the 5° and 8° lines, some of the newest wells (not shown on the map, which was made in 1925) occurring in still steeper parts of the monocline. Nevertheless, the steep monocline here also is the general eastern boundary of the field, because, if for no other reason, in a short distance eastward it brings the productive zone to the surface.

Productive area.—The productive area ranges in width from $2\frac{1}{2}$ to 3 miles and is marked at the surface by the outcrop of the Pierre shale with regular westward dips ranging from $2\frac{1}{2}°$ to 5°, averaging approximately 3°. The productive area extends from the steep monocline west to the outcrop of the massive Trinidad sandstone. The same regular westward dip continues another 3 miles farther west to the bottom of the main syncline, but within these last 3 miles, the underlying Pierre shale, covered by coal-bearing rocks at the surface, seems to be comparatively barren of oil.

Although it has been said that the oil in this area occurs in faults, faults in the productive area are notably absent. In the steep monocline some faulting has taken place, but no faults were found in the field west of the steep monocline. Numerous small local flexures, however, traverse the Pierre shale approximately east and west and locally disturb the prevailing direction of strike and dip. The largest of these might show 6 feet of vertical displacement from crest to trough. They were conscientiously recorded wherever found, and appear on the structure map as little anticlinal axes, mentioned in the legend of the map as "small anticlinal flexures."

Jointing in the shale is generally difficult to discern, but is adequately recorded here and there in the thin sandstone beds of the upper Pierre. The trend of most persistent jointing (the most frequently discovered and in many places the most prominent) is approximately S. 50° E. A broad syncline, or direction of strain, trending southeast like this persistent jointing, is suggested by a swing of the contours on the structure map (Plate 1), for example, in the vicinity of Sec. 11, T. 20 S., R. 69 W., where it is distinctly noticeable.

Jointing directions cannot readily be measured in the massive Trinidad sandstone west of the productive area. Such joints as appear have irregular S-shapes both horizontally on dip slopes and vertically in cliff faces. It is as if the strains recorded by the thin sandstones interbedded in the Pierre shales were not great enough to produce a regular pattern of joints in the overlying thick beds of massive sandstone.

tion that is here put forth. It is simply this: when (in Eocene time) the Pierre shale of the Florence field was deformed by the main geosynclinal folding complicated locally by the steep monocline, it was held between competent beds. Below it are the Niobrara limestones and the "Dakota group" sandstones, and above it were the Trinidad sandstone and overlying Vermejo coal-bearing sandstone series. Stresses, that were thus stored up (possibly) in the less competent Pierre shale, were released by the erosion of the Trinidad and Vermejo sandstones, and found relief in strains. Thus, possibly, the little anticlinal flexures were formed; possibly subsurface joints already existing were opened as fissures; or possibly the open fractures were newly formed at this time. The oil accumulated in the fissures.

ORIGIN OF OIL

A scheme like the foregoing tacitly postulates that the accumulation of the oil in the fissures—the commercial accumulation—was very recent, as recent as the present topography. Such a scheme fits best with the idea that the oil is indigenous to the Pierre shale, through which it is disseminated, accumulating in pools only as the fissures are formed.

Although the detailed evidence is here omitted, the mapping showed clearly that the boundary between the Pierre shale and the overlying coal-bearing sandstone series is not a constant horizon. Undoubtedly the uppermost Pierre at the north end of the Florence area is equivalent to sandstone above the Pierre shale at the south. It is well known that the shales corresponding with Pierre are much thinner in southwestern Colorado than in either the northern or the eastern parts of the state, and the idea that the upper part of the thicker shales is of the same age as the coal-bearing sandstones above the thinner shale in the southwestern section is not a new one. In the Florence area the northward fingering-out of the sandstone into shale is pronounced. It is a fair inference that during the deposition of a considerable part of the upper Pierre in this vicinity coal was forming in swampy land some tens of miles on the southwest. If the oil at Florence originated in the Pierre shale in which it is found, these near-shore conditions may have a bearing on its origin.

From a different point of view, the Niobrara beds might possibly be considered a source of the oil at Florence. The Niobrara formation is bituminous throughout the Rocky Mountains, and oil shale is widespread in it. The plentiful bituminous matter in the Niobrara outcrops of the Florence vicinity was noted by Washburne.[1] One who favors a metamorphic origin of oil might reject the less bituminous Pierre as a source

[1] *Op. cit.* (1910), p. 519.

rock, and theorize that the oil was generated by the folding from bituminous matter in the Niobrara, migrating upward into the fissures of the Pierre shale. In this connection it is worth mention that the average carbon ratio of the Cretaceous coals here mined is approximately 57 per cent.

In structures such as the Salt Creek dome, Wyoming, and the Iles dome, Colorado, oil occurs in fissures in shale immediately above producing sands or sands that probably contained oil at one time. The theory is held that some of the oil originally trapped in the sand migrated upward into the shale and still remains there.[1] By analogy it has been claimed that the Florence field is a remnant of oil once trapped in the Dakota sandstone below.[2] This seems improbable to the writer because of the absence of structure sufficient to cause great accumulation in the sandstone, and because the theory demands the upward migration of oil through approximately 1,200 feet of beds, including members as dense as the Greenhorn limestone, the Carlile sandstone, and the Timpas limestone. As far as tested, these 1,200 feet are now practically barren of oil.

No other possible source of oil appears unless it is the very old marine sediments beneath the pre-Morrison unconformity. The theory that the oil migrated from them into the Pierre shale encounters the same difficulties previously mentioned, still further magnified.

PROPERTIES OF OIL

An analysis of a Florence oil is given in Table III. The analysis was made at the laboratory of the Standard Oil Company (Indiana) in Casper,

TABLE III

ANALYSIS OF FLORENCE CRUDE OIL

Gravity, Bé	30.1°	Gasoline, per cent	7.0
Sulphur, per cent	0.34	Kerosene, per cent	12.0
Water	None	Gas oil, per cent	16.0
Cold test	51°	Heavy, per cent	63.8
Initial	198°	Coke, per cent	1.2

Wyoming. The crude oil came from Travis No. 6, Sec. 28, T. 20 S., R. 69 W., in the southern part of the field.

[1] C. H. Wegemann, "Oil and Gas in Colorado," *Production of Petroleum in 1924, Amer. Inst. Min. Met. Eng.*, pp. 174–75.

[2] It is noteworthy, however, that the same theory of upward migration from far below was held as early as 1891. See bibliography.

The gravity of the oil throughout the field is nearly the same, that is 30°–31° Bé. No water is found in it, and the wells never go to water.

A complete description of the oil is given by Washburne.

TABLE IV

STATISTICS ON FLORENCE AND CAÑON CITY FIELDS, JANUARY 1, 1928*†

	Florence Field	Cañon City Field
Past total production of field, barrels	11,875,423	149,951
Productive area of field, square miles	12–20	2
Present number producing wells	58	21 (Feb. 1, 1928)
Present daily production for field, barrels	590	583 (Feb.)
Minimum daily well production, barrels	½	....
Life of wells, years	1–33	....
Total number of wells drilled	1,007 approx.	45 approx.
Maximum total production of any one well, barrels	622,000	....
Ratio—producers to dry holes	1:2.5	....
Maximum depth of producing well, feet	3,600	2,154
Minimum depth of producing well, feet	1,100	910
Gravity of oil, Degrees Baumé	29–30	30–33
Gasoline content, per cent	7 (distillation)	3
Open hole commonly drilled, feet	1,500	....
Total well cost, cable tools exclusively	\$6,000–\$15,000	Contract \$10,000 1,600 feet on pump
Mud and paraffin cleaning frequency, months	12	....
Field price of crude	Mid-Continent plus slight premium	....
Deepest well drilled, feet	4,500	3,560
Carbon ratio in bituminous coals (Cretaceous), per cent	57	....
Distance to coal mines, miles	½–3	½–2
Distance of coal beds above oil horizons, feet	2,200–3,400	Probably same
Vertical stratigraphic producing range, feet	500	Probably same
Stratigraphic interval productive zone above Dakota sandstone, feet	1,900–2,400	Probably same
Stratigraphic interval productive zone above Niobrara shale, feet	1,000–1,500	Probably same
Average per well per day for February, 1928, barrels	10.42	27.77

* From pamphlet, *A Trip through the Florence and Cañon City Oil Fields, March 17, 1928, for the Rocky Mt. Assoc. Petrol. Geol., et al.,* (1928). See bibliography.

† Production is less than 3 barrels per foot of hole drilled.

CAÑON CITY FIELD

In 1926 oil was discovered in the Cañon City field on Arkansas River between Cañon City and Florence. Figure 4 shows the development that had taken place by April, 1928. In February, 1928, average daily production of the Florence field was 590 barrels; of the Cañon City field, 583 barrels.

The occurrence in the Cañon City field is the same as at Florence.

The oil comes from fissures in the Pierre shale, but the structure is different. An anticlinal nose plunges southward through the Cañon City field, and the oil seems to follow its general trend. As in the Florence field, producing wells are not found very far beyond the first-line outcrops of massive coal-bearing sandstones, which here extend east and west and form the south boundary of the field. Southward the thickness of overlying beds increases greatly in a short distance.

CONCLUSIONS

1. The oil at Florence occurs in fissures in the Pierre shale.

2. The oil is found in a belt 3 miles wide on the eastern limb of a geosyncline. A steep monocline forms the eastern boundary of the field because it allows the oil to escape and brings productive beds to the surface.

3. The western boundary of the field coincides approximately with the heavy overlying coal-bearing sandstones. It may be that the removal of the overburden allows fissures to open in the Pierre shale, into which the oil collects.

4. No faults were found in the productive area.

5. Probably the oil originated in the Pierre shale or in the underlying Niobrara beds.

6. The new Cañon City field is a similar occurrence. The oil-bearing fissures in the Pierre shale are localized on the trend of a southward-plunging, anticlinal nose.

BIBLIOGRAPHY

1885

M. C. Ihlseng, "Report on Oil Fields of Fremont County," *Colorado State Sch. Mines Ann. Rept.*, pp. 75–88.

1888

J. S. Newberry, "The Colorado Oil Fields," *Eng. and Min. Jour.*, Vol. 46, pp. 498–99.

1889

J. S. Newberry, "The Oil Field of Colorado," *Sch. Mines Quart. (Columbia)*, Vol. 10, pp. 97–102.

———"The New Oil Field of Colorado and Its Bearing on the Question of the Genesis of Petroleum," *Trans. N.Y. Acad. Sci.*, Vol. 8, pp. 25–28.

1891

Arthur Lakes, "The Fuel Resources of Colorado," *Amer. Geol.*, Vol. 8, pp. 16–17.

1892

G. H. Eldridge, "The Florence Oil Field, Colorado," *Trans. Amer. Inst. Min. Eng.*, Vol. 20, pp. 442–62.

1901

Arthur Lakes, "The Geology of the Oil Fields of Colorado," *Bull. Colorado State Sch. Mines*, Vol. 1, pp. 221–26.

1902

Arthur Lakes, "Oil in Colorado," *Mines and Minerals*, Vol. 22, pp. 256–57.

1904

N. M. Fenneman, "The Florence, Colorado, Oil Field," *U. S. Geol. Survey Bull. 260*, pp. 436–40.

1905

N. H. Darton, "Preliminary Report on the Geology and Underground Water Resources of the Central Great Plains," *U. S. Geol. Survey Prof. Paper 32*, pp. 344, 380–81.

1906

N. H. Darton, "Geology and Underground Waters of the Arkansas Valley in Eastern Colorado," *U. S. Geol. Survey Prof. Paper 52*, pp. 12–36, 38–43.

1910

Chester W. Washburne, "The Florence Oil Field, Colorado," *U. S. Geol. Survey Bull. 381*, pp. 517–44. (With bibliography. All references to Washburne in the text refer to this bulletin.)

———"The Cañon City Coal Field, Colorado," *U. S. Geol. Survey Bull. 381*, pp. 341–78.

1915

F. W. Foote, "The Florence, Colorado, Oil Field," *Mexican Min. Jour.*, Vol. 19, pp. 48–49.

1917

W. T. Lee, "Geology of the Raton Mesa and Other Regions in Colorado and New Mexico," *U. S. Geol. Survey Prof. Paper 101*, pp. 162–69.

1921

W. H. Emmons, *Geology of Petroleum* (McGraw-Hill Book Co.), pp. 429–31.

1922

M. R. Campbell, "Guidebook of the Western United States, Part E, The Denver and Rio Grande Western Route," *U. S. Geol. Survey Bull. 707*, pp. 66–72.

1924

C. A. Fisher, "Petroleum Development in the Rocky Mountain States during 1923," *Production of Petroleum in 1923, Amer. Inst. Min. Met. Eng.*, p. 58.

1925

C. H. Wegemann, "Oil and Gas in Colorado," *Production of Petroleum in 1924, Amer. Inst. Min. Met. Eng.*, p. 168.

1928

A pamphlet entitled *A Trip through the Florence and Cañon City Oil Fields, March 17, 1928, for Visiting Members of the American Association of Petroleum Geologists, by Courtesy of the Cañon City Chamber of Commerce, the Florence Chamber of Commerce, the Continental Oil Company, the Midwest Refining Company, the Texas Production Company, and the Rocky Mountain Association of Petroleum Geologists.*

E. R. Lilley, *The Geology of Petroleum and Natural Gas* (D. Van Nostrand Co.), pp. 367.

Tolbert R. Ingram, "Geologists Visit Florence Field, Second Oldest Oil Discovery," *Oil and Gas Jour.*, Vol. 26, No. 48 (April 19, 1928), pp. 156–57.

RELATION OF ACCUMULATION TO STRUCTURE IN NORTHWESTERN COLORADO[1]

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ABSTRACT

The producing structures of northwestern Colorado are: (1) Iles dome, (2) Moffat or Hamilton dome, (3) Tow Creek anticline, (4) Thornburg dome, (5) Rangely dome, (6) White River dome, and (7) Hiawatha dome. Other seemingly favorable structures have been drilled and found barren. The producing formations range in age from Jurassic to Eocene. Oil and gas accumulation in northwestern Colorado is evidently caused by anticlinal structure. The nature of the hydrocarbons in the different structures and the lithology of the strata in which they occur indicate that the causes of accumulation were not common to all and that the folding and uplift to which they were subjected may have been factors in forming the oil and gas from the original organic material as well as being the agents of accumulation.

INTRODUCTION

The producing structures of northwestern Colorado are seven in number; they are: Iles dome (oil and gas), Moffat or Hamilton dome (oil), Tow Creek anticline (oil), Thornburg dome (gas), Rangely dome (gas and some oil), White River dome (gas), and Hiawatha dome (gas).

The producing horizons range in age from Jurassic to Eocene. The relation of these structures to the major structural features of the region are shown on the regional map of northwestern Colorado (Fig. 1).

There are a great many structures[2] in this area which are not shown on the map. Some of them have been drilled and found barren, for no apparent reason, since the structures are similar and the section identical with those which produce.

STRATIGRAPHY

The generalized geologic column in northwestern Colorado is given in Table I. Brief discussions of the formations which contain oil and gas follow.

JURASSIC

Nugget sandstone.—This formation is also called White Cliff and is the lower producing horizon in the Iles and Moffat domes, where it is

[1] Manuscript received by the editor, October 22, 1928.

[2] For another published description of part of the area, see J. D. Sears, "Geology and Oil and Gas Prospects of Part of Moffat County, Colorado, and Southern Sweetwater County, Wyoming," *U. S. Geol. Survey Bull. 751-G* (1924).

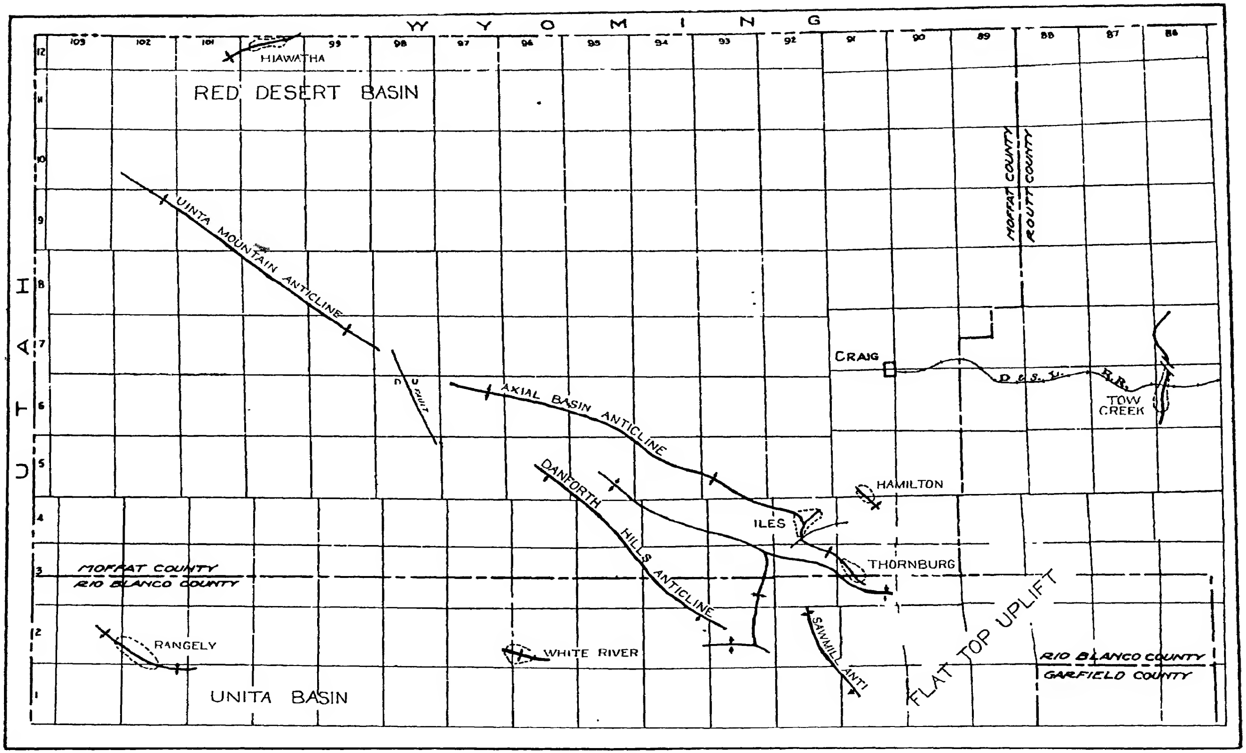

FIG. 1.—Map showing relation of producing structures to major structural features of northwestern Colorado. Length of area mapped, approximately 110 miles.

called the "Sundance sand." It is a clean quartz sand, white, gray, or pink, very cross-bedded and is probably of aeolian origin, although subsequently worked by water. There is a zone of red or pink shaly material near the top in most localities, and the formation thickens from 250 feet

TABLE I

General Section of Formations in Northwestern Colorado

Period	Series	Formation
Tertiary	Miocene	Browns Park
	Eocene	Green River Wasatch
Cretaceous	Upper	Laramie Lewis Mesa Verde Mancos Dakota
	Lower(?)	Morrison
Jurassic		Twin Creek or Sundance Nugget or White Cliff (Sundance sand)
Triassic		Red-beds. In some localities separable into Ankareh, Thaynes, and Woodside formations
Permian and Pennsylvanian		Park City
Pennsylvanian		Maroon beds, present only in Flat Top uplift Weber quartzite Lime, shale, and sand series, unnamed
Mississippian		Limestone, equivalent to Madison
Devonian		Limestone, unnamed
Cambrian		Quartzite
Algonkian(?)		Quartzite
Archean		Granites, schists, and gneisses

in the Flat Top area to more than 900 feet in the Uinta Mountain region. It overlies unconformably red beds of probable Triassic age.

Twin Creek formation.—This is of marine origin and corresponds with the Sundance of Wyoming. It overlies the "Sundance sand" of the Iles field but pinches out before reaching the outcrop on the flanks of the Flat Top uplift. At the type locality at Sundance, Wyoming, there is a sand

a few feet thick at the base of the formation which is correlated with the Nugget. Thus arose the name "Sundance sand" in the Iles field.

The trend of the shore line of the Jurassic sea was northeast and southwest, and passed southeast of the Thornburg dome if not through the dome itself. The formation thickens northwestward toward the center of the basin. There are only a few feet of black and gray shales of the Twin Creek beds in the well which penetrated them on the Thornburg dome, but at Iles there are 35–50 feet which can be allotted to the Twin Creek. In the Uinta Mountain region, the thickness is 150 feet or more; and the formation is composed of black and gray shales, thin sandstones, and limestones containing characteristic Sundance fossils.

It is the writer's belief that this formation contains the source beds for the oil found in the "Sundance sand" and probably the Morrison sand on Iles dome and in one well on Moffat dome. There is a sufficient thickness of the Twin Creek shales on these structures to supply large quantities of oil under favorable conditions, and the thinning of equivalent beds on the Thornburg dome may account for the small quantity of oil found in the "Sundance sand" in the one well which penetrated it on that structure.

The increasing thickness of the Twin Creek beds on the northwest may or may not mean an increasing thickness of source beds. On the Rangely anticline, which should be underlain by 125 or more feet of this formation, a well reached the top of the "Sundance sand" and found it barren. The Rangely anticline is much larger and has more closure than the Iles dome.

LOWER CRETACEOUS(?)

Morrison formation.—The age of the Morrison is not definitely known, although it is usually placed doubtfully in the Lower Cretaceous. It is considered a fresh-water deposit but has a remarkable persistency in lithology and thickness throughout wide areas. The upper two-thirds of the formation is composed of light gray and varicolored shales. The lower part contains several prominent sandstones which are non-uniform and discontinuous. Oil and gas are encountered in some of these sands in the Iles and Moffat fields. A prominent sand in the upper part of the lower Morrison can be correlated with fair accuracy between the Iles, Moffat, and Thornburg domes, and is the most important producer in the Morrison formation on Iles dome. The Morrison is 450–500 feet thick in northwestern Colorado.

UPPER CRETACEOUS

Dakota sandstone.—The Dakota in this area maintains its tripartite division as recognized in practically all of the Rocky Mountain region.

The upper sand is a very prominent marker, having a thickness ranging from 50 to 80 feet, and is buff or gray in color. The lower sand is more variable and in many places is interstratified with considerable thicknesses of gray and greenish shales. The base of the lower sand is everywhere conglomeratic. The medial shales are gray and in places greenish in color, wherein they differ from the shales of most other localities, which are ordinarily dark gray to black and in places contain thin coal beds. The total thickness of the Dakota ranges from 125 to 200 feet.

The Dakota is the producing sand of many oil fields in the Rocky Mountain region, and it was formerly considered useless to test deeper sands between it and the Pennsylvanian. The Dakota is the principal producer of oil on the Moffat dome, contains gas in the Thornburg dome, but was barren in the Iles dome, except for small amounts of gas and a little low-grade oil.

Mancos formation.—This formation is 5,100 feet thick and is composed of gray and black shales in almost its entire thickness. The Mancos includes equivalents of the Benton, Niobrara, and a part of the Pierre of eastern Colorado, but they are all so nearly alike in northwestern Colorado that no attempt has been made to separate them in mapping. Typical Mowry shale, as recognized in Wyoming, is found on the outcrops almost immediately above the Dakota sandstone. Approximately 400 feet above the Dakota there is a limy sandstone, ordinarily only a few feet in thickness, which probably corresponds with the position of the Frontier in Wyoming, and is here designated as such. Within the first 300 or 400 feet above the Frontier, there are limy streaks in the shale, some very light colored and containing typical Niobrara fossils. The upper part of the Mancos is very sandy and contains several thin sands which are ordinarily not traceable except for short distances. The exception is the Morapos sand which occurs approximately 800 feet below the top of the Mancos and serves as a key bed in mapping the surface structure on the Iles and Moffat domes. The basal part of the Mancos shale, which is equivalent to lower Benton, is considered by most geologists as containing the source beds for the oil and gas encountered in the Dakota sand. Three wells on the Iles structure have produced considerable oil from this zone, which is 75–100 feet above the base of the Mancos.

Mesa Verde formation.—The Mesa Verde is predominately a sandstone formation, containing many beds of sandy and carbonaceous shales, together with valuable coal beds in its upper part. It is of fresh- or brackish-water origin and ranges in thickness in northwestern Colorado from 3,000 to 4,500 feet. It has no importance as a producer of oil and gas in northwestern Colorado; but as it furnishes small production in other

parts of the Rocky Mountain region it cannot be classed as barren in this district.

Lewis shale.—This formation is similar in lithology to the greater part of the Mancos, being composed of gray and drab shales. The Lewis, together with the underlying Mesa Verde and upper part of the Mancos, is the approximate equivalent of the Pierre shale of the Front Range. It reaches thicknesses of more than 1,000 feet in the eastern part of northwestern Colorado, but is absent in the western part because of pre-Eocene erosion, which removed the overlying Laramie, the Lewis, and in some places a part of the Mesa Verde.

Laramie formation.—The Laramie is composed of massive sandstone and sandy shales with a few unimportant coal beds. It reaches a thickness of more than 1,500 feet but occurs only in the northern part of the territory under discussion. So far as known, it has no importance as a prospective producer of oil or gas.

EOCENE

Wasatch formation.—The Wasatch is of continental origin, and its lithology differs in different places. In general, the upper and lower parts of the formation are predominantly sandstone, and most of the middle part is composed of brilliantly colored shales. It also contains a few minor coal beds. The thickness ranges from 3,500 to 5,000 feet, and the formation lies unconformably on beds which range in age from Mesa Verde to Laramie. The upper part of the Wasatch contains the gas sands of the White River dome, and those of the Hiawatha dome are probably in the lower part of the formation.

Green River formation.—The Green River overlies the Wasatch conformably and is recognized by a marked change from the bright-colored shales of the Wasatch to the light-gray, greenish, and nearly white shales, oölites, and sandstones of the Green River. This formation carries the oil shales of western Colorado, eastern Utah, and southwestern Wyoming. The richer shales occur in the middle part of the formation; and the lower part contains lean shales, several prominent sandstones, and a few thin limestones. The upper part is marked by a preponderance of massive, very lenticular sandstones. No production has thus far been discovered in the Green River, although it has been tested in the Uinta basin of Utah. Veins of gilsonite and other natural asphalts occur in eastern Utah, and a small amount of free oil is derived from a tunnel into the formation near the town of Dragon. Oil saturation is common in the sands of both the Wasatch and Green River formations.

MIOCENE(?)

Browns Park formation.—Unconformably overlying all older formations in northwestern Colorado is the Browns Park, which is doubtfully placed in the Miocene period. It is composed of soft, light-colored sandstone with some conglomerate. Its principal importance lies in the fact that it conceals the lithology and structure of the older formations in a large part of northwestern Colorado.

STRUCTURE

ILES DOME

Iles dome (Fig. 2) has approximately 500 feet of closure. It is on the main axis of the Axial Basin anticline and probably owes its existence to the presence of a large fault on its southern edge with the downthrow on the north. Near the top of the structure the steeper dip seems to be on the southeast, but lower on the west side the strata dip steeply to conform with the attitude of the beds all along the south side of the Axial Basin anticline. This structure is unique in comparison with others in the vicinity in that it is cut by numerous faults of considerable magnitude. The northernmost fault has a displacement of 575 feet where it cuts the escarpment of the Morapos sandstone in the eastern part of Section 13, but it gradually disappears in the northern part of Section 15. The upthrow is on the north. The largest fault affecting this structure is on its southern edge, and in Section 25 has a displacement of approximately 1,100 feet. The downthrow is on the north and becomes less toward the west, the displacement disappearing before it reaches the main axis of the anticline. In the steeply dipping zone on the west side there are two faults with a down-block between them. Their displacements grow less toward the east, and the faults disappear shortly after crossing the main axis of the anticline.

Subsurface contours on the Dakota sand show that the top of the dome is very similar to that shown on the surface map except that the highest point has shifted a little more than $\frac{1}{4}$ mile southeast (Fig. 3). It also indicates that a small fault, with the downthrow on the northwest, crosses the northwest corner of Section 23.

The Iles dome is the most important producer in northwestern Colorado, the runs for July, 1928, averaging 2,130 barrels per day with some of the wells pinched in. There are three producing horizons, namely, the shale zone, 75–100 feet above the Dakota, the Morrison sand, and the "Sundance sand." Three wells are at present producing from the shale, six from the Morrison, and four from the "Sundance." The production

figures, as given on the maps (Figs. 2 and 3), are not initial but represent an average throughout the first few weeks of production. On top of the

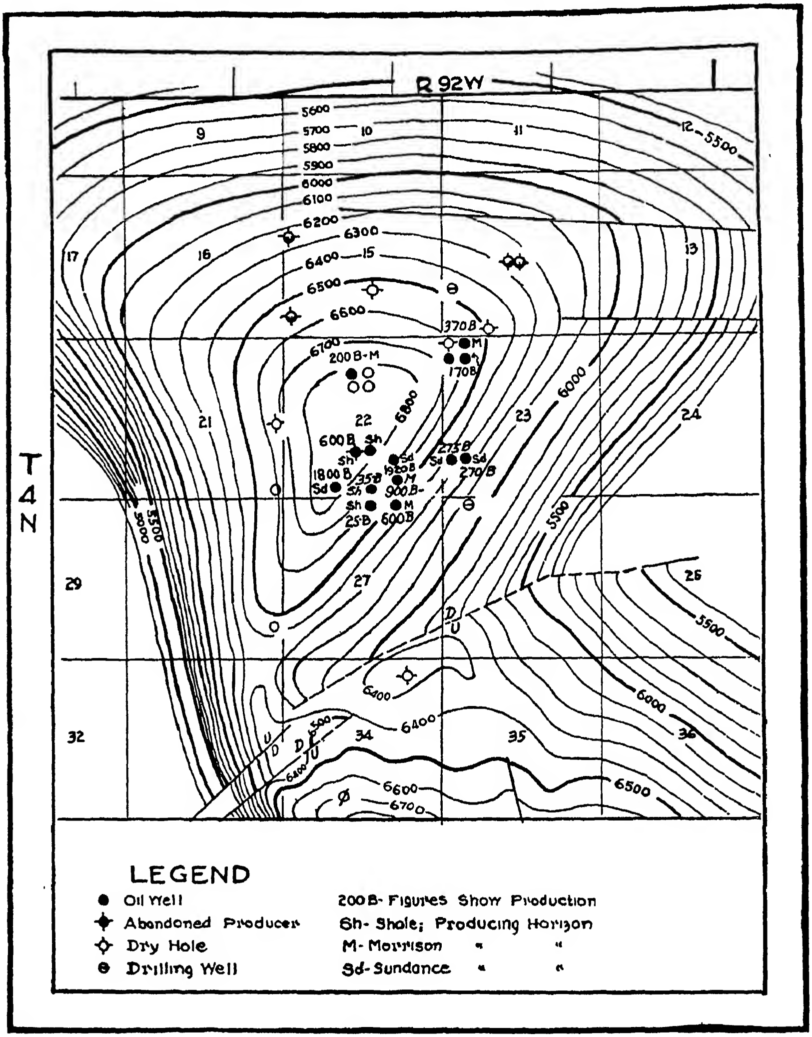

FIG. 2.—Structural map of Iles dome, showing surface contours on Morapos sandstone. Contour interval, 100 feet. Width of area mapped, approximately $4\frac{1}{2}$ miles.

structure the shale horizon is reached at a depth of 2,550 feet, the Dakota sand at 2,600, the Morrison at 3,050, and the "Sundance" at 3,225 feet.

The Dakota sand, which had previously been demonstrated as the main oil horizon of the Moffat or Hamilton dome, contained water, only a little gas, and small amounts of low-grade oil on the Iles dome.

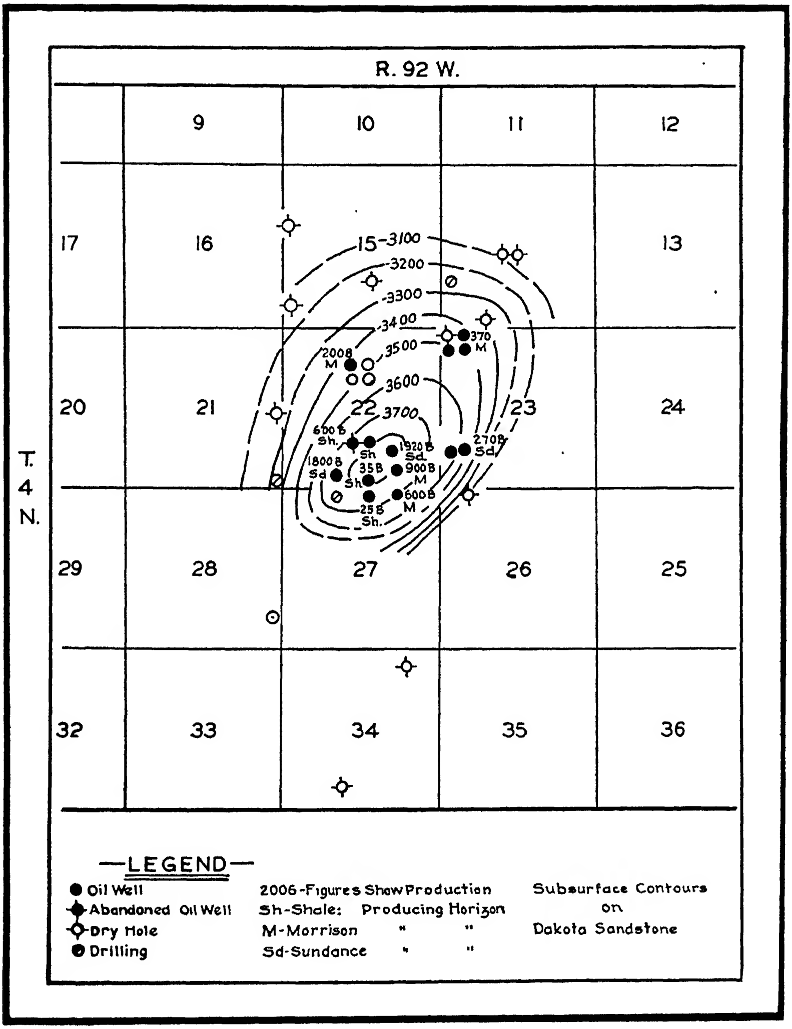

FIG. 3.—Structural map of Iles dome, showing subsurface contours on Dakota sandstone. Contour interval, 100 feet. Width of area mapped, approximately $4\frac{1}{2}$ miles.

The productive area on Iles dome is confined to the top of the structure as shown by the subsurface contours, and the largest wells are high-

est, structurally. Wells on top of the structure encountered flows of gas in the Morrison sand varying from 3,000,000 to 7,000,000 cubic feet daily. Farther down on the flank of the structure, the Morrison produces both oil and gas.

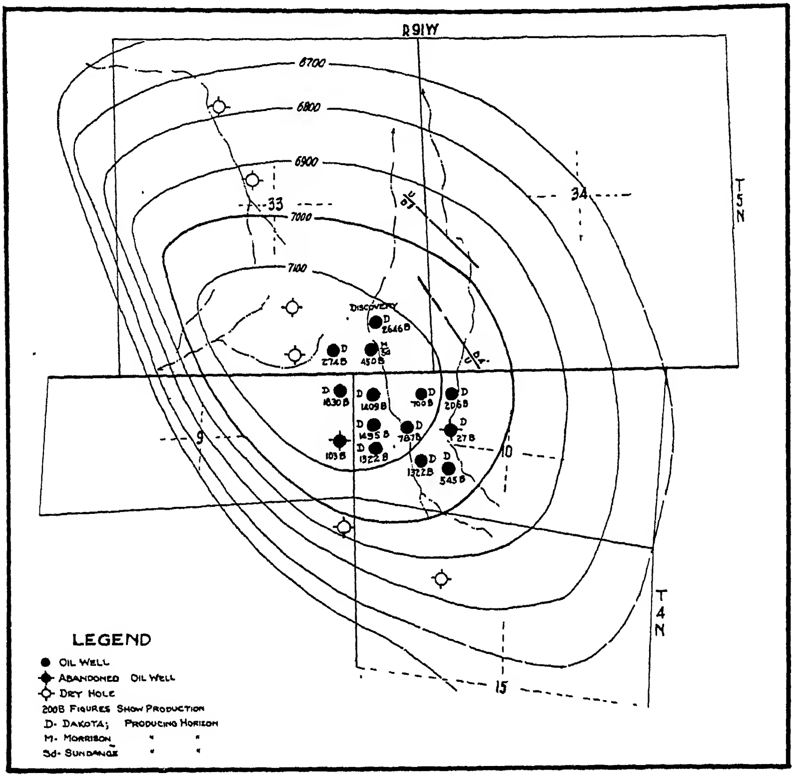

FIG. 4.—Structural map of Moffat dome, showing surface contours on Morapos sandstone. Contour interval, 100 feet. Width of area mapped, approximately $2\frac{1}{4}$ miles.

MOFFAT OR HAMILTON DOME

This is a very pronounced domal structure (Fig. 4) with the axis elongate northwest and southeast. It has a closure of 500 feet with the steep dip on the southwest, as steep as 30°. The structure is encircled by an escarpment of Morapos sandstone, which occurs at a horizon in the Mancos shale, 800 feet below the base of the Mesa Verde formation. This is the only key bed for structural work, the center of the structure being a covered area of Mancos shale; and if faulting of any magnitude

cuts the crest of the dome, it is obscured. Two minor faults, having displacements of 4 and 5 feet, cut the Morapos escarpment on the east side of the structure and possibly increase in magnitude with depth. They may have been factors in forming accumulation channels from the source beds to the Dakota, which is the reservoir sand. It is assumed by most geologists that the source beds for oil in the Dakota sand are in the lower part of the overlying Benton shale, which is here included in the Mancos.

Because only a small area has been drilled on the Moffat dome, a subsurface map does not accompany this paper, since it would show only that the subsurface crest moves a short distance toward the southeast as in the Iles dome. Thirteen wells have produced from the Dakota on this structure, and one which encountered water in that sand was deepened and encountered oil in both the Morrison and "Sundance" sands. On the top of this structure, the Dakota is reached at 3,800 feet, the Morrison at 4,250, and the "Sundance" at 4,450 feet. The order in which the wells were drilled controlled more or less the initial production, and it may be that the two dry holes, shown within the top contour, would have been producers if drilled previous to those farther southeast. Water encroachment evidently follows closely upon the exhaustion of oil from the top of the structure. It is evident, however, that the largest wells were located on the very top of the dome, as shown by subsurface elevations on the producing sand. The average daily production from the Moffat dome during July, 1928, was 1,140 barrels.

THORNBURG DOME

Thornburg dome, sometimes called Morapos (Fig. 5), has a closure of approximately 900 feet, with the long axis trending northwest and southeast. It is on a southeast continuation of the Axial Basin anticline and has its steeper dips on the southwest. From a syncline which marks the limit of the closure on the southwest, all of the formations rise rapidly toward the Saw Mill anticline, which is an extension of the main Flat Top uplift. Here all of the older Paleozoic formations are exposed.

Due to the absence of key beds, this structure was detailed by means of shale dips; and no actual faulting on the outcrops was seen except for several small faults on the north end of the structure. Minor faulting on most of the structure, especially along its crest, is evidenced by the plentiful occurrence of calcite slabs which have been weathered from faulted fissures.

Aside from small amounts of oil from the Frontier in the northernmost well and from the "Sundance" in the southern well, nothing except

gas has been produced from this structure. All three of the wells encountered gas in the Dakota sand in the amounts shown on the map. The

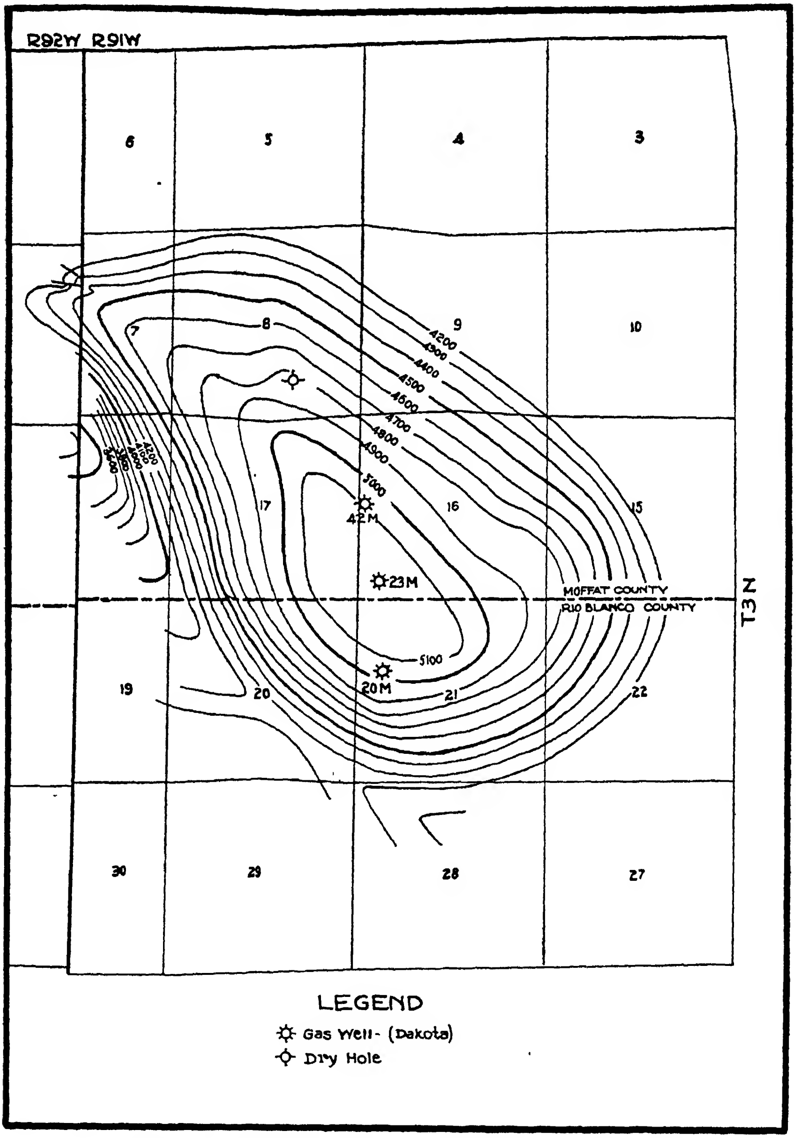

FIG. 5.—Surface structural map of Thornburg dome, detailed by means of shale dips. Contour interval, 100 feet. Width of area mapped, approximately 4 miles.

first well drilled was the largest, and the last was the smallest. The difference may have been due to the order in which they were drilled, but was very possibly due to the difference in sand porosities. The gas is confined to the top of the structure, as shown by a water well in the Dakota approximately 300 feet below the top contour. The Dakota sand on top of the structure was reached at a depth of 1,950 feet.

After the discovery of oil in the "Sundance" on the Iles dome, the southern well on the Thornburg dome was deepened to that formation but encountered only small amounts of oil. It is fairly certain that this was due to a stratigraphic change between the two structures rather than to a difference in the relation of the structures themselves.

RELATION OF THE ILES, MOFFAT, AND THORNBURG DOMES

A comparison of these three producing structures is very interesting, especially with regard to the oil and gas content of the Dakota sandstone.

It is difficult to understand why, with identical formations involved, the Dakota should contain large quantities of high-grade oil in the Moffat dome, gas in the Thornburg dome, and only a little gas and a little low-grade oil at Iles. The discovery well at Moffat flowed at the rate of 4,500 barrels per day when first drilled, and settled to approximately 2,600 barrels. The oil had a gravity of 37° Bé. The discovery well on Thornburg was estimated as an 80,000,000-foot gas well, but some time later gauged at 42,000,000. The early history of drilling on Iles dome was marked by discouraging results, and the only production was from small wells in lowest Mancos or equivalent of the Benton shale, 75–100 feet above the Dakota. Operators were seriously considering the abandonment of the field when the deepening of one of the wells resulted in the discovery of gas in the Morrison and a 2,000-barrel well in the "Sundance."

The outstanding differences in the three structures are shown by the relations of the Dakota sand to sea-level. The sea-level datum elevation of the Dakota is 2,980 feet on the Moffat dome, 3,800 feet on the Iles, and 5,000 feet on the Thornburg.

These structures occupy a position in an area which was doubtless affected by two movements, those of the Axial Basin anticline and the Flat Top uplift. The latter lies on the south and east; and upon it all of the older formations, including the pre-Cambrian granite, are exposed. The age of the Flat Top uplift is at least as late as post-Eocene, and it is thought that the Axial Basin anticline was formed, at least in its later stages, at approximately the same time. It seems reasonable to suppose that conflicting forces were set in motion in the region affected by both

uplifts, resulting in the formation of the three structures under discussion and also of the faults of large displacement associated with the Iles dome. The upthrow of the largest fault is on the south or toward the Flat Top, the region of greatest uplift.

The presence of oil and gas is evidently due to structure in these places, but there is a question as to whether it is there as a result of accumulation according to the anticlinal theory or as a result of other factors. By a simple application of the anticlinal theory, all three of these structures should contain oil in the Dakota, if any of them do. We have no reason for doubting that the source beds are present and were originally of similar nature, as far as organic content is concerned, in all three structures. It is further evident that free oil as such must have been present in the strata during the process of folding, which took place in Tertiary time. If we subscribe to the theory that free petroleum may be formed from organic matter in the shales by a slow process of metamorphism in flat-lying beds, due, in part at least, to the weight of younger strata, we must further assume that this process, after reaching the stage of the formation of oil, would go farther and eventually reach the respective stages of higher-grade oil, oil and gas, gas only, and perhaps a last stage of complete dissipation of the hydrocarbons. It would be a remarkable coincidence if the folding of these three structures had been timed so as to catch them at the first, third, and fourth stages respectively, as previously mentioned.

Obviously, the Dakota sand was originally at approximately the same level in all three localities. It now lies 2,020 feet and 820 feet higher in the Thornburg and Iles domes, respectively, than in the Hamilton dome. It seems probable that there is a relation between the total upward movement and the present form of the hydrocarbons. The Thornburg dome, which has undergone the greatest amount of differential movement, contains gas; the Hamilton dome contains oil in the Dakota; and the Iles dome produces oil from the shale which is presumed to contain the source beds in all three structures, although conditions were evidently not favorable for its accumulation in the Dakota on the Iles dome.

These observations lead to the theoretical conclusion that the folding and differential upward movement formed the oil and gas out of whatever organic substance existed prior to that time, and subsequently the structures themselves were the agents of accumulation.

There are numerous features regarding the accumulation of oil in the three sands of the Hamilton and Iles domes that seem to defy any reasonable explanation. The "Sundance sand" is directly in contact with over-

lying marine beds which may be considered as a source of oil. The Morrison sand is separated from these beds by 150 or more feet of shales and lenticular sands of fresh-water origin (Fig. 6). Some means of vertical migration must have been instituted unless the fresh-water strata contain source beds. This may have been brought about along faults, and, after reaching the reservoir sand, moved toward the top of the structure. Other sands occur between the main producer of the Morrison and the source beds, but they are lenticular and may not have had sufficient continuity to allow migration to the top of the structure. It is difficult to perceive, however, why this explanation, if applicable to the Morrison sand, should not apply also to the Dakota, since we know that the lower Benton shale contains oil.

TOW CREEK ANTICLINE

The Tow Creek anticline is 18 miles in length, only a part of which is shown on the accompanying map (Fig. 7). There are several hundred feet of dip on each flank, but the amount of effective closure is relatively slight, probably not being more than 200 or 300 feet. The northern part of the anticline

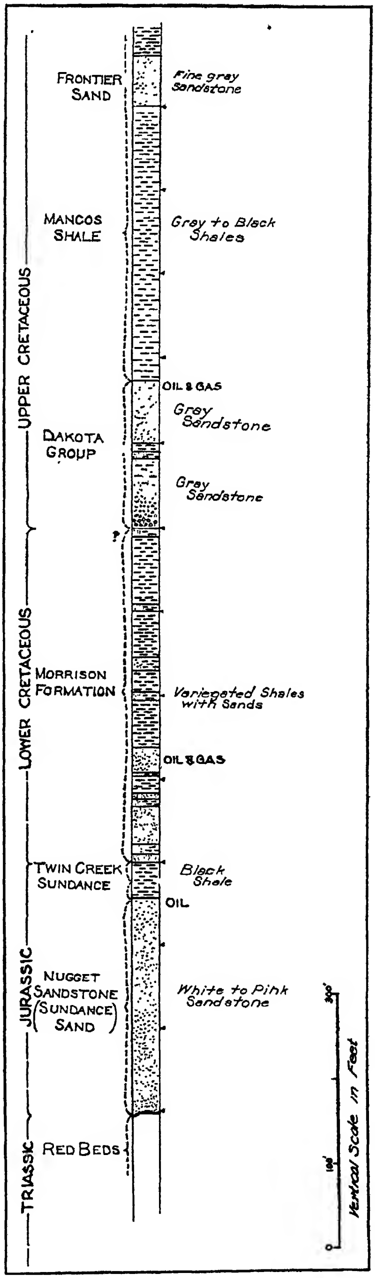

FIG. 6.—Graphic representation of formations from lower Mancos to the upper Red-beds in the Moffat, Iles, and Thornburg region.

is cut by igneous intrusions of quartz-porphyry and basalt dikes, and the structure as a whole may be of laccolithic origin.

The production in the Tow Creek anticline is from a zone in the Mancos shale approximately 600 feet above the Frontier and 1,000 feet above the Dakota sand. The area of greatest production seems to be immediately east of the anticlinal axis. The accumulation is probably due to a fractured zone in the shale and it seems significant that the best wells are located in that part of the anticline where the steep east dip begins. Accumulation according to the anticlinal theory probably does not apply on this structure. The principal value of the structure lies in the fact that it creates a fractured zone in the shales and brings the producing horizon within reach of the drill. Two wells have tested the Frontier and Dakota sands and found them to contain water.

The average daily production for Tow Creek during the month of July, 1928, was 700 barrels. The producing stratum is encountered on top of the structure at approximately 2,600 feet, the Frontier sand at 3,150 feet, and the Dakota at a little deeper than 3,500 feet.

RANGELY DOME

The Rangely dome is situated in the northwestern part of Rio Blanco County, Colorado, a short distance from the Utah line. It is a large closed dome 12 miles long, with its axis extending northwest and southeast (Fig. 8). It has a closure of more than 1,200 feet; and the surface formation is the Mancos shale, surrounded by an escarpment of the lower Mesa Verde sandstone. A small amount of oil has been produced for many years from a shallow horizon in the Mancos shale on the southwest side of the structure, at the upper edge of the steeply dipping beds. Several deep tests have been drilled which found the Dakota sand to contain gas. Four gas wells to this sand have been completed, but only one was gauged and showed a production of 74,000,000 cubic feet per day. All four of the gas wells are near the top of the structure. One of these was deepened to the Nugget or "Sundance sand," and it was found to contain water. Wells farther down on the structure also contained water in the Dakota.

It is very evident that the presence of gas is due to structural conditions. It is significant also that the small production of oil from shale in this structure is confined to the steeply dipping zone on the southwest side of the structure, where fracturing of the shales would most likely be found.

The question arises as to the differences, whether structural or otherwise, on the Rangely dome where the "Sundance sand" contains water and on the Iles dome where it contains oil. The marine Jurassic beds are

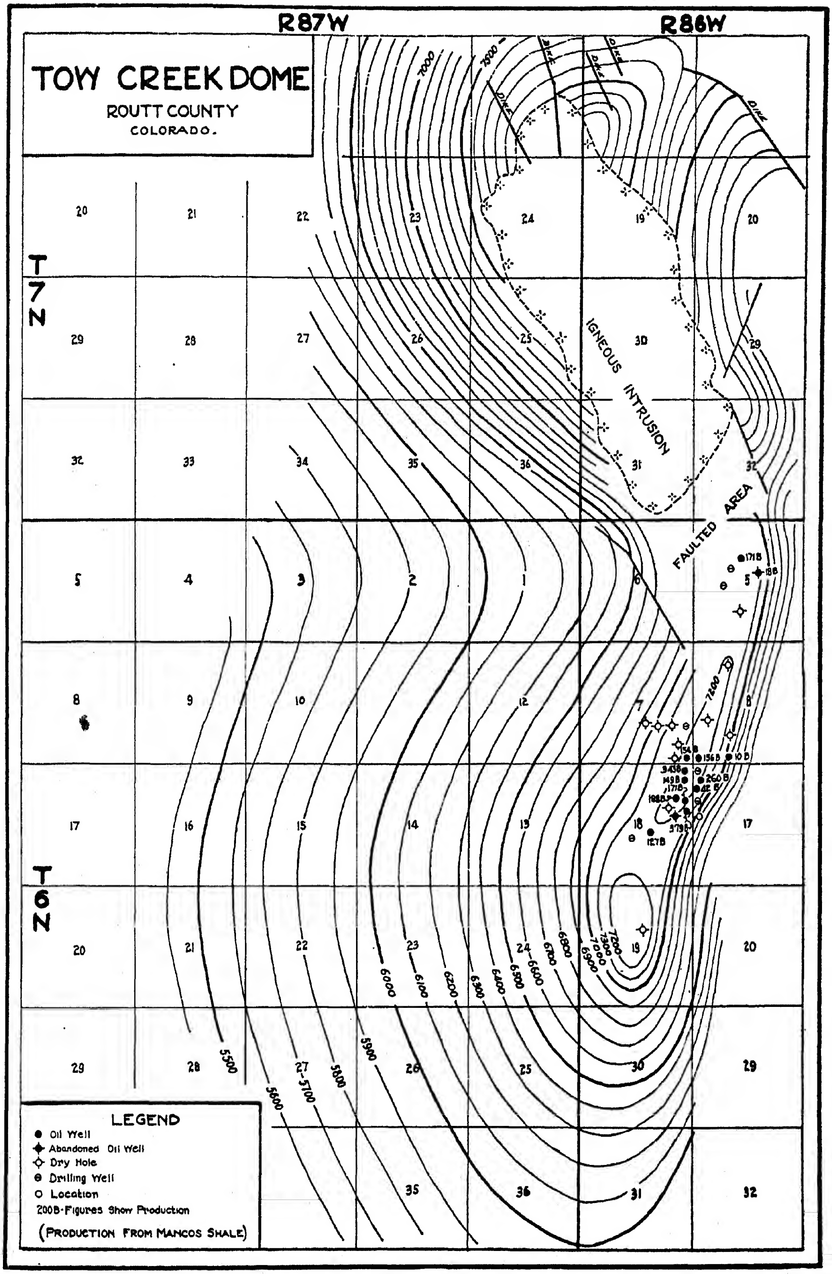

FIG. 7.—Surface structural map of a part of Tow Creek anticline. Contour interval, 100 feet. Width of area mapped, approximately 7 miles.

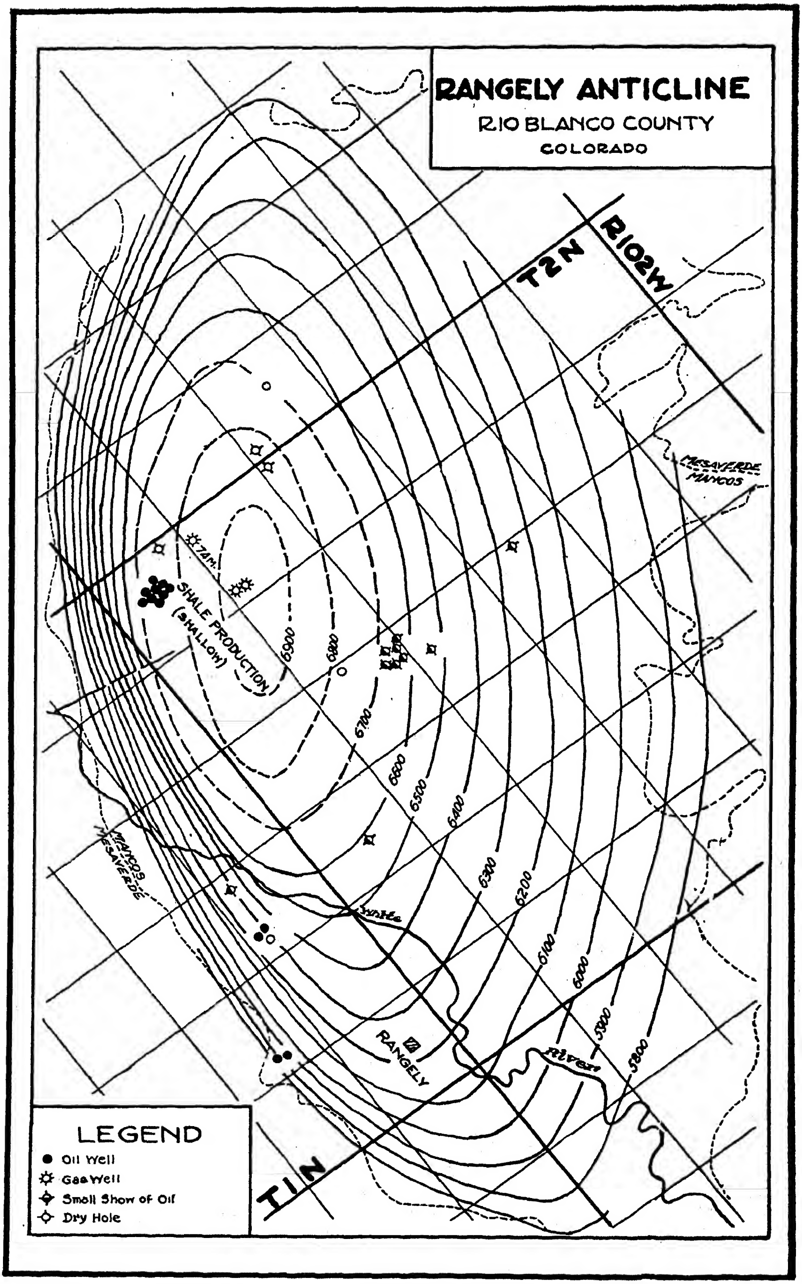

FIG. 8.—Surface structural map of Rangely anticline. Contour interval, 100 feet. Width of area mapped, approximately 7 miles.

present in both areas, although with different relations to the shore line of deposition. The locality of the Iles dome was nearer to the shore line, and conditions more favorable for the formation of source beds may have been present.

Structurally, the principal difference is that the Iles dome is profoundly faulted. Too much significance should not be given to this feature, however, since the Moffat dome which also contains oil in the "Sundance" is, so far as known, very slightly disturbed by faulting. The age of folding of the two structures was probably the same, and the most reasonable explanation for the absence of production in the "Sundance" on the Rangely dome is the hypothesis of different depositional conditions in different parts of the marine Jurassic sea.

WHITE RIVER DOME

The White River dome is situated on the north edge of a large Tertiary basin, has a slight elongation east and west, and has a closure of 400 feet (Fig. 9). The steeper dips are on the south, and the surface formation is Wasatch of Eocene age. The Wasatch formation is 4,000 feet thick in this locality, 1,000 feet of which has been eroded from the top of the dome.

Shallow gas was discovered on this structure in the year 1890. About 1918, three other wells were drilled, one of which had a very good showing of light oil. In 1923 and 1924, a well was drilled to 2,700 feet but was abandoned before reaching the base of the Wasatch. All of these wells were drilled near the top of the structure, and all of them produced gas from sands in the Wasatch at depths ranging from 600 to 900 feet. The initial flow of these wells varied from 2,000,000 to 15,000,000 cubic feet per day. The identity of the source beds from which this gas was derived is not known. It is usually assumed that the gas originated in the Wasatch beds themselves, but there are minor faults near the top of the structure which may be so deep seated as to allow upward migration from the underlying marine beds of the Cretaceous.

The gas wells are near the top of the structure; and the smallest gas well, which also contains some oil, is lowest. No wells have been drilled far enough down on the flanks of the dome to determine whether or not the gas area is surrounded by a zone in which water occurs in the same sands.

HIAWATHA DOME

The Hiawatha structure (Fig. 10) lies partly in Wyoming and partly in Colorado. The surface formation is Wasatch; and the structure pro-

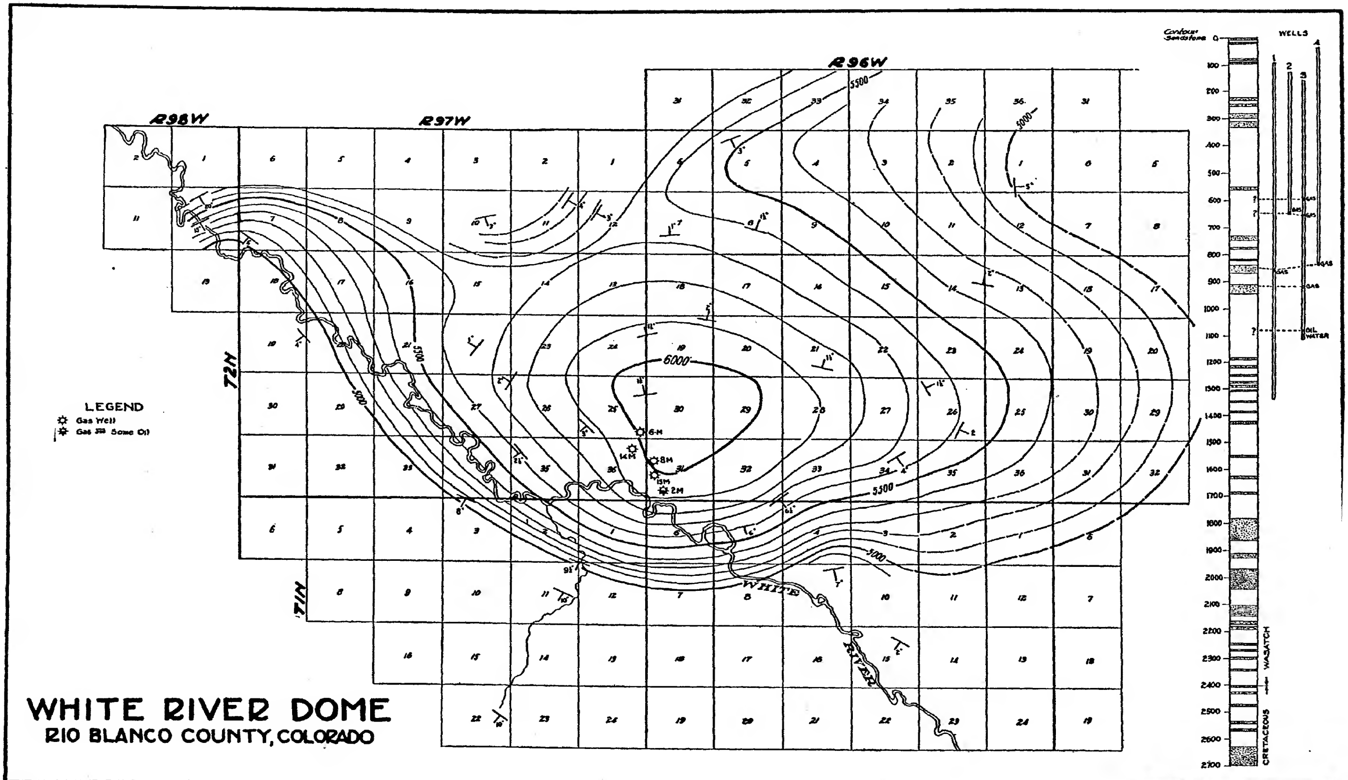

FIG. 9.—Surface structural map of White River dome, contoured on Wasatch sandstone. Contour interval, 100 feet. Width of area mapped, approximately 16 miles. (By P. B. Whitney.)

duces gas from three wells, the initial production ranging from 56,000,000 to 100,000,000 cubic feet per day. The gas is piped to Salt Lake City.

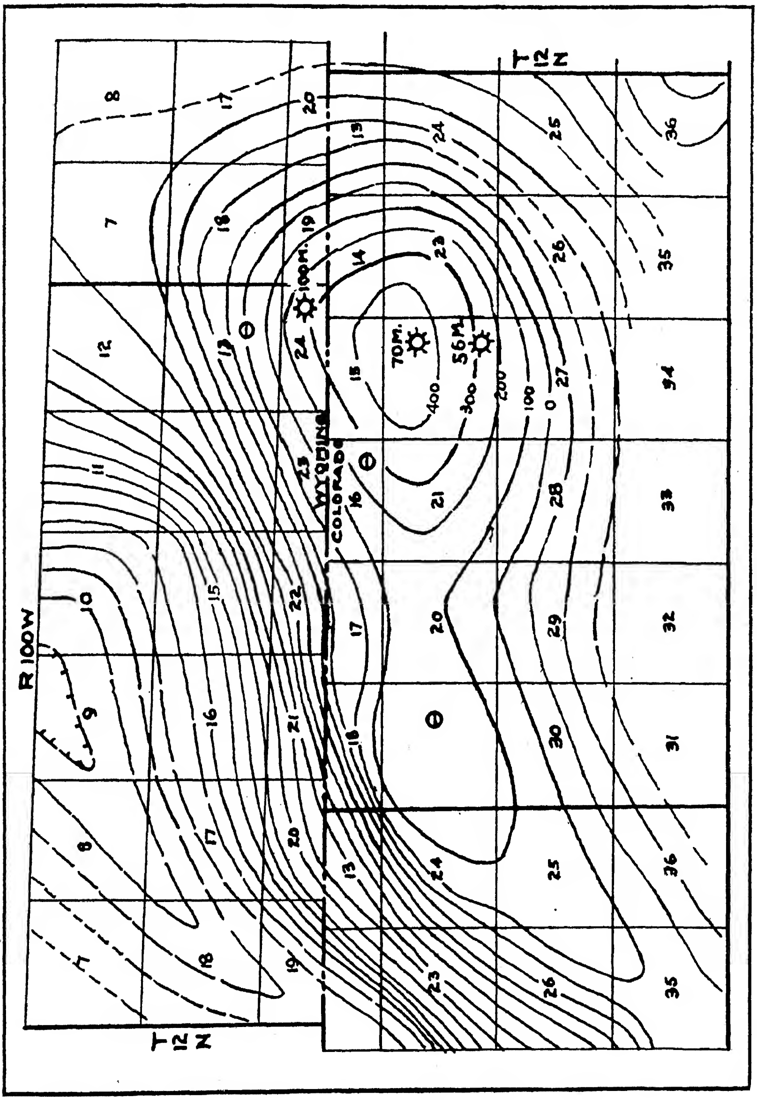

FIG. 10.—Surface structural map of Hiawatha dome, contoured on Wasatch formation. Contour interval, 100 feet. Width of area mapped, approximately 8 miles.

The Hiawatha dome has its long axis east and west and lies on the edge of the Red Desert Tertiary basin, bearing somewhat such a rela-

tion to it as does the White River dome to the Uinta basin. It has a closure of more than 400 feet, and the steep dip is toward the north. The age position of the producing horizon is not exactly known but is probably in the base of the Wasatch or possibly in the top of the underlying Cretaceous series. The gas area, as far as it is defined at present, is on top of the structure, although one well has recently been reported to have a very favorable showing of high-grade oil at approximately the same structural elevation as the largest gas well. The sands are lenticular, and it is difficult to correlate from well to well.

SUMMARY

Accumulations of oil and gas in commercial quantities in northwestern Colorado are very evidently due to the presence of anticlinal or domal structures.

The nature of the hydrocarbons in the different structures and the lithology of the strata in which they occur indicate that the causes of accumulation were not common to all and that the folding and uplift to which they were subjected may have been factors in forming the oil and gas from the original organic material as well as being the agents of accumulation.

In the Moffat and Iles fields, the accumulation of oil and gas in the Dakota, Morrison, and "Sundance" sands is confined to the top of the structures and is surrounded by water which, due to hydrostatic pressure, encroaches upon the oil area as the latter is exhausted.

In the Thornburg, Rangely, White River, and Hiawatha structures, the gas seems to be present only in the top; and where it occurs in the Dakota sand, as at Thornburg and Rangely, it is under hydrostatic pressure. The relation of gas to water in the White River and Hiawatha structures is still unknown.

Shale oil in the Tow Creek anticline, Iles dome, and Rangely dome occurs as an indirect result of anticlinal structure. The accumulation, and possibly the change from the source material to oil, probably resulted from the establishing of zones of fracturing when the beds were folded. It is significant that the shale oil occurs at the point of major change of dip.

THREE TYPICAL OIL FIELDS OF THE ILLINOIS REGION[1]

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Urbana, Illinois

ABSTRACT

The cross sections, maps, and other data presented in this paper give the essential facts about the Centralia district in south-central Illinois, the Martinsville pool in east-central Illinois, and the Francisco pool in southwestern Indiana. In the Centralia and Francisco areas, pronounced domes in the Pennsylvanian beds mark similar but more pronounced domes in the underlying Mississippian beds. In the Martinsville area, only a slight suggestion of the lower Mississippian folding is shown by the overlying beds.

In general, the oil accumulation has taken place on the high parts of the several anticlines and domes. Locally, irregular sand conditions have modified this relation so that the limits of the producing areas do not exactly conform to the structural contours.

INTRODUCTION

The descriptions of typical oil fields of the Illinois region given in this paper are the results of independent investigations by the writers. The work in Illinois was undertaken as a part of the regular program of the Illinois Geological Survey, and statements of the results have appeared in publications of the Survey.[3] The study of the Francisco field, Gibson County, Indiana, was a private investigation for Mann and Huber of Evansville, Indiana.

In this paper, general information from numerous reports of the state geological surveys and the U. S. Geological Survey has been used freely. Details regarding conditions in each of the typical pools discussed have been obtained from the acknowledged sources and from a study of well data from the several fields.

PHYSIOGRAPHY

The area shown on the generalized structure map (Fig. 1) is drained by Mississippi, Ohio, Illinois, and Wabash rivers and their tributaries.

[1] Read before the Association at the Tulsa meeting, March 25, 1927. Manuscript received by the editor, November 18, 1927. Presented with permission of M. M. Leighton, chief, Illinois Geological Survey.

[2] Illinois State Geological Survey.

[3] A. H. Bell, "Structure of Centralia and Sandoval Oil Fields, Illinois," *Illinois State Geol. Survey, Illinois Petroleum No. 10* (July 23, 1927); Gail F. Moulton, "Areas for Further Prospecting near the Martinsville Pool, Clark County," *Illinois State Geol. Survey, Illinois Petroleum No. 4* (August 28, 1926).

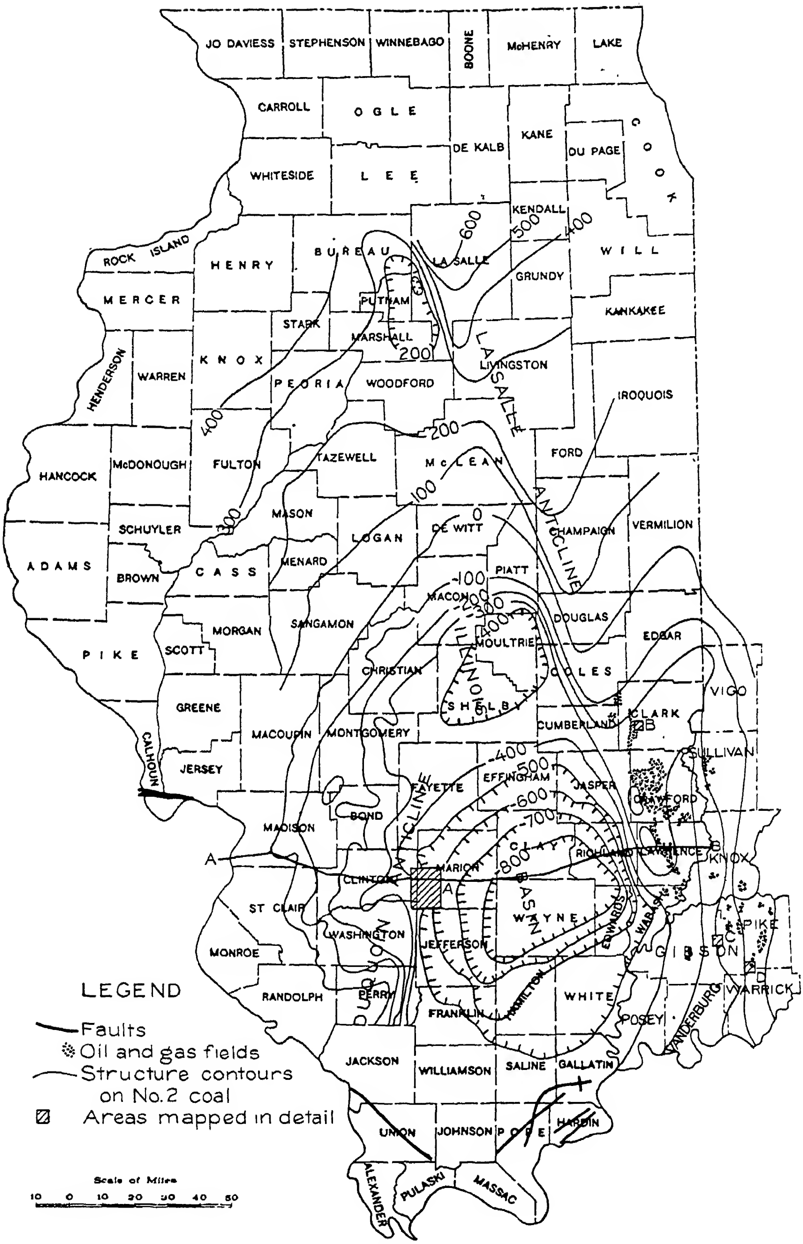


FIG. 1.—Generalized structure map of Illinois and southwestern Indiana, showing oil and gas fields. The Illinois basin, extending north and south through the center of the state, is flanked on the east by the La Salle anticline and on the west by the Duquoin anticline.

The country is characterized by gently rolling topography with an extensive cover of Pleistocene glacial débris over consolidated strata. Most of the area is so slightly dissected that useful outcrops are rare.

GENERAL STRUCTURE

The regional structure (Fig. 1) is shown by rather general contours drawn approximately on the No. 2 coal of Pennsylvanian age. Only the larger, more pronounced structural features are indicated.

The general form of the structure is a broad shallow basin which is crossed by the La Salle anticline in the eastern part and the Duquoin fold in the south-central part. The La Salle anticline extends from central-northern Illinois slightly east of south to Lawrence County in the southeastern part of the state. Although the fold is rather steep on both sides in north-central Illinois, the dips, particularly on the east flank, become less and less toward the south. As a result, in Crawford County the east dip is of minor importance; and on the south in Wabash County there is only a flat structural terrace lying above, and east of, the steep west dip which is a prolongation of the west limb of the fold.

The Duquoin fold as now known has a general north-south trend and a steep dip toward the east from an area in which the strata are horizontal or dip gently toward the west. Between the La Salle and Duquoin uplifts lies the deepest part of the Illinois-Indiana coal basin, which has been called the Illinois basin.

The structural and stratigraphic relations as determined from data now available for a section from the vicinity of St. Louis, Missouri, to a point near Vincennes, Indiana, are shown by Figure 2. The location of this section is indicated by line *A-B* on Figure 1.

An eastward dip from the Ozark uplift and a westward dip from the Cincinnati uplift into the Illinois basin are the principal structural features brought out by this section. The deepest part of this basin a short distance west of the eastern Illinois oil fields, and the two general anticlines on which the more important oil fields have been discovered are also shown.

The most striking stratigraphic feature shown by the section is the general eastward increase in thickness of the strata shown. The most important increases are in the thickness of the Devonian-Silurian limestone series and of the Pennsylvanian. The former is probably due to pre-Mississippian erosion in western Illinois, which in some places reduced the Devonian-Silurian limestones to a thickness of less than 100 feet. The change in thickness of the Pennsylvanian beds is probably to be

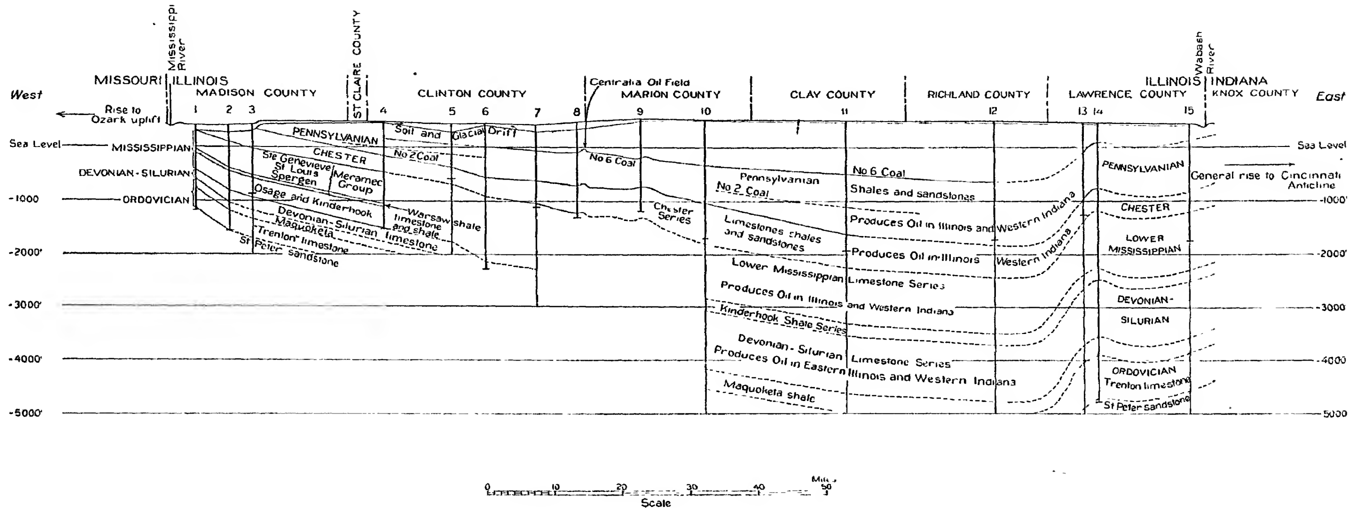


FIG. 2.—Generalized structural cross section from St. Louis, Missouri, to Vincennes, Indiana. Depths shown in feet. Location of section is shown in Figure 1 (*AB*).

1. Granite City well, Sec. 24, T. 3 N., R. 10 W.
2. Look No. 1, Sec. 1, T. 3 N., R. 9 W.
3. Killer No. 1, Sec. 8, T. 3 N., R. 8 W.
4. Reiman, Sec. 8, T. 2 N., R. 5 W.
5. J. O. Kock, Sec. 24, T. 2 N., R. 4 W.
6. P. Herzog, Sec. 23, T. 2 N., R. 3 W.
7. M. E. Johnson, Sec. 25, T. 2 N., R. 2 W.
8. A. L. Thomas, Sec. 13, T. 2 N., R. 1 W.
9. Lorenzen, Sec. 33, T. 2 N., R. 2 E.
10. Williams, Sec. 24, T. 2 N., R. 3 E.
11. Curry, Sec. 8, T. 2 N., R. 7 E.
12. Olney, Sec. 12, T. 3 N., R. 10 E.
13. Caudle No. 3, Sec. 36, T. 4 N., R. 13 W.
14. J. R. Middaugh No. 23, Sec. 32, T. 4 N., R. 12 W.
15. Boonillet, Sec. 33, T. 4 N., R. 10 W.

ascribed to the presence of a considerable basin in central Illinois at the time of their deposition, in which deposition did not take place in western Illinois until beds of considerable thickness had been deposited on the east.

Although post-Devonian–pre-Mississippian erosion and post-Mississippian–pre-Pennsylvanian folding, faulting, and erosion have been determined in some Illinois localities, there is no evidence now available that either the Duquoin or La Salle anticlines were loci of uplift before the end of lower Mississippian deposition. These structural features are evidently the near-surface expression of zones of movement in the more competent Cambrian and pre-Cambrian rocks a mile and more below the surface, probably contemporaneous with the structural disturbances which gave rise to the extensive faulting and folding in southern Illinois during the Carboniferous and at the end of the Paleozoic.

On the La Salle anticline near the Clark County oil fields, the pre-Pennsylvanian deformation seems to have been more pronounced than the post-Pennsylvanian deformation. Farther south, in southwestern Indiana and in Lawrence County, Illinois, the largest part of the deformation along the trend of the La Salle anticline occurred in post-Pennsylvanian time, as is shown by the essential parallelism of the Pennsylvanian and Chester beds.

In western Illinois important folding occurred during and after the Pennsylvanian.

GENERAL LOCATION OF OIL FIELDS

The principal oil fields of eastern Illinois and southwestern Indiana are located east of the steep west dip of the La Salle anticline. The largest and most productive pools have been found in Illinois, where the effect of the major structural feature is most pronounced. The distribution of these pools along the La Salle anticline has been determined by the coincident occurrence of local structural conditions and proper stratigraphic conditions. The pools thus far discovered are on the southern quarter of the anticline in areas from which the Mississippian was not entirely removed by pre-Pennsylvanian erosion, and in which the Pennsylvanian strata are generally 400 feet or more in thickness. A few favorably located tests on structures on the north failed to find production.

Some of the Clark County pools described by Mylius[1] accumulated in hills of weathered Mississippian limestone, buried beneath Pennsyl-

[1] L. A. Mylius, "Oil and Gas in East-Central Illinois," *Illinois State Geol. Survey Bull. 54* (1928).

vanian strata. These are the only buried hills known in Illinois at the present time which have had an effect on oil accumulation.

The upper part of the Devonian-Silurian limestone series has also been subjected to weathering and erosion on the La Salle anticline from Clark County north. The pools producing from this horizon near Martinsville, Illinois, and in the area 20 miles south of Terre Haute, Indiana, found the limestone moderately weathered. Farther north, where the limestone has been honeycombed through weathering agencies, only showings of oil with much water were found, suggesting that the oil might have been flushed out. Farther south this weathering was not effective, and no oil is to be expected at this horizon.

The only commercial oil production from limestones in Illinois other than from the weathered type mentioned has been obtained from oölitic limestones, principally in Lawrence County. The original texture of the limestone probably provided the porosity and permeability requisite for a satisfactory reservoir bed.

The principal Illinois oil fields other than those in the general area of the La Salle anticline are located on the seeming continuation of the Duquoin anticline. These are the fields of the Centralia district. Although the generalized structure map shows that the Duquoin fold is continuous for a considerable distance, the detailed studies in the area for which data are available show that local doming is present and that the oil pools of the Centralia district are located on such local structures.

Information on the structure and typical sand conditions for the following areas shown in Figure 1 is presented in detailed discussion: (1) The Centralia and Sandoval fields of central Illinois; (2) the Martinsville pool in Clark County, eastern Illinois; (3) the Francisco pool, Gibson County, sourthwestern Indiana. The map also shows the location of (4) the Tri-County field in southern Pike County, southwestern Indiana, which is the subject of a paper by R. E. Esarey.[1]

Structure of Centralia and Sandoval Oil Fields, Illinois

By A. H. Bell

Introduction

This paper contains the description of an area about 100 square miles in extent, situated in the southeast part of Marion County and adjacent part of Clinton County. It includes the Sandoval pool and several smaller

[1] R. E. Esarey, "Tri-County Oil Field of Southwestern Indiana," *Structure of Typical American Oil Fields*, Vol. 1 (1929), pp. 23–24.

productive pools, which in order of importance are (1) Wamac, (2) Junction City, (3) Langewisch-Kuester, and (4) Brown. Brief preliminary reports on all except the Sandoval pools have been published.[1] For the Sandoval field the only published information[2] was the result of a study made when only two of the producing wells had been drilled; hence it could include few details of the structure. Since that time oil has been produced from approximately 100 wells in the Sandoval pool, and the results of a study of all of the available data are embodied in the present paper.

ACKNOWLEDGMENTS

The writer is under obligation to the oil and coal operators of the district for placing at his disposal the information that rendered the work possible. Joseph H. Markley, Jr., acted as field assistant. Former publications of the Illinois Geological Survey have been freely drawn upon, chiefly for information about the history of development.

PHYSIOGRAPHY

The physiography of the region is not described in this report because it is controlled by Pleistocene glacial deposits and the thickness of these deposits obscures the structure of the Paleozoic rocks.

HISTORY[3]

"The discovery and use of oil from a seep in the mine of the Marion County Coal Company, Sec. 30, T. 2 N., R. 1 E., attracted oil operators to this section of the state. The seep in the mine came through a fault. . . . ."

The Marion County Oil and Gas Company drilled a well on the Sherman farm in Sec. 29, T. 2 N., R. 1 E., half a mile east of the shaft of the mine. The well was completed by November 1, 1908, with only a showing of oil in a sand immediately below No. 6 coal (now known as the Dykstra sand). Three other wells were drilled just southwest of the Sherman well on the Dykstra farm in Section 32. These had an initial production of 18 barrels a day each after shot, and by the end of 1908 their production had declined to 3 barrels a day each.

[1] A. H. Bell, "Oil Investigations in the Centralia Area—Preliminary Report," *Illinois State Geol. Survey, Illinois Petroleum No. 4* (August 28, 1926), pp. 6–12; "Oil Investigations in the Centralia Area—Preliminary Report Concluded," *ibid., No. 5* (October 16, 1926), pp. 1–10.

[2] R. S. Blatchley, "Illinois Oil Resources," *Illinois State Geol. Survey Bull. 16* (1910), pp. 130–46.

[3] R. S. Blatchley, "Illinois Oil Resources," *Illinois State Geol. Survey Bull. 16* (1910), pp. 130–32.

The latter part of 1908 was a time of considerable leasing activity in the region. A north and south direction of leasing was maintained upon the supposition that an oil field in this locality would naturally parallel the La Salle anticline. In the early spring of 1909 the L. Stein No. 1 well was drilled in Sec. 5, T. 2 N., R. 1 E. The shallow sand found in the Dykstra wells was not reported in this well, but a sand producing oil was found at 1,404 feet and was named the Stein sand. A thickness of 22 feet was reported, and the yield was 50 barrels per day. Meantime, the Benoist No. 1 well of the Southwestern Oil and Gas Company was being drilled in the NE. cor., Sec. 8, T. 2 N., R. 1 E. This well was located 1,200 feet southeast of Stein No. 1. It found only a showing of oil in the Stein sand, and drilling was continued. At 1,528 feet it struck what is known as the Benoist sand which gave gas and oil. The upper 12 feet of the sand contained gas having a pressure of 370 pounds per square inch. The lower part of the sand from 1,540 to 1,546 feet yielded 200 barrels of oil per day.

In the succeeding years about 150 wells were drilled in an area of 6 square miles around the discovery well, and a boundary of production was found on all sides.

STRUCTURE

Regional folding.—The Centralia-Sandoval area is situated a little west of the center of the Illinois structural basin, and, accordingly, the regional dip is toward the east. At the south and southwest is the Ozark highland, a geanticline of major importance and extent. About 70 miles northeast is the La Salle anticline. In many localities throughout southern Illinois the rock strata have been affected by gentle folding and in some places by faulting. One of the most pronounced of these gentle folds is the Duquoin anticline, or, more accurately, monocline.[1] It is known to extend for a distance of 20 miles north from Elkville to a point 2 miles east of Dubois closely parallel with the Illinois Central Railroad. Certain well-defined structural features of the Centralia-Sandoval area are approximately in line with the axis of the Duquoin anticline, though it is not known whether the latter fold is continuous across the intervening gap of 18 miles.

Detailed folding.—Detailed subsurface structure of the Pennsylvanian strata in the Centralia-Sandoval area is shown in Figure 1 by means of contours representing the elevations of Herrin (No. 6) coal with reference to sea-level. The depth of the coal was obtained from well logs and mine

[1] D. J. Fisher, "Structure of Herrin (No. 6) Coal Seam near Duquoin," *Illinois State Geol. Survey Report of Investigations No. 5* (1925), p. 24.

surveys at as many points as possible. Elevations were determined by plane-table survey.

The boundaries of mine workings have been indicated on the map by shaded lines. Elevations had been determined by the mine engineers in only one of the five mined areas, namely the Centralia Coal Company's mines Nos. 2 and 5 south of Centralia. For the Marion County Coal Company's Glen Ridge mine at Junction City, elevations were determined by an underground plane-table survey by the writer's party. For the other three mined areas, namely at Odin, Sandoval, and the Centralia Coal Company's mines Nos. 3 and 4, underground elevations had not been determined; and since none of these mines had been in operation for several years, it was not possible to enter them. The best available information was that given from memory by former engineers and superintendents of the mines. It consisted of estimates of percentage grades in different parts of the mines, and these formed the basis for determining the position of some of the contours in Figure 1.

The regional dip of the Paleozoic strata in the Centralia-Sandoval area is toward the east. For Herrin (No. 6) coal it ranges from 35 feet per mile across the southern part of the area to 20 feet per mile across the northern part. The maximum dip for the area (in Centralia Coal Company's mine No. 5) is 140 feet in half a mile (5.3 per cent, or 3°).

Two conspicuous structural features are shown in Figure 3. One, the Centralia monocline, is a north-south belt of relatively strong east dip which is associated with a fault zone of similar trend. The most continuous fault is about 6 miles long. The upthrow is on the east; the maximum displacement of 110 feet occurs in Sec. 7, T. 1 N., R. 1 E., east of the shaft of the Centralia Coal Company's mine No. 4. The displacement decreases northward and southward from this place. The other conspicuous feature is a series of anticlines and synclines with an east-west alignment, interrupted by the Centralia monocline. The best example is the Sandoval anticline which seems to be a feature of an east-west trending fold rather than of the north-south Duquoin fold.

Two cross sections from east to west (Fig. 4) show the attitude of No. 6 coal and illustrate the fault with the downthrow on the west.

Two structure maps were drawn for the Sandoval area, one with No. 6 coal as the key horizon and the other on the Benoist sand which is here 930 to 980 feet below No. 6 coal stratigraphically (Figs. 5 and 6). These two maps show closed anticlines of essentially similar outline and trend. The chief difference between them is that the dips are in most directions more pronounced on the sand than on the coal.

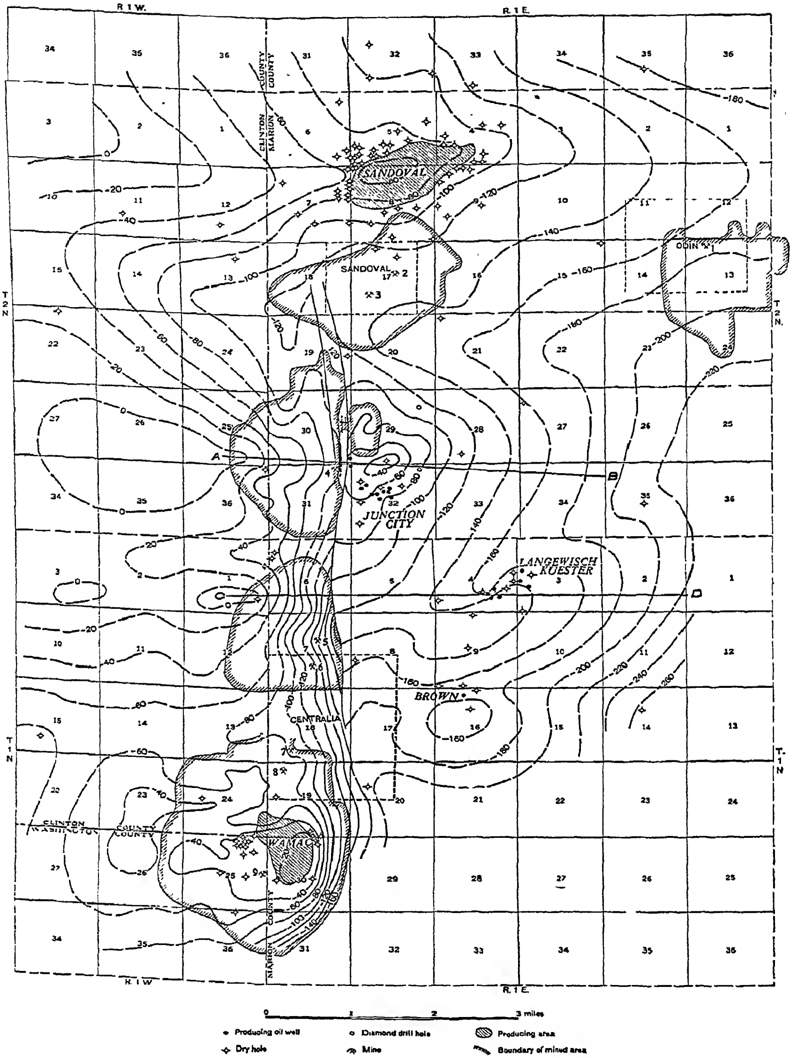


FIG. 3.—Structure map of the Centralia-Sandoval area. Key horizon, top of Herrin (No. 6) coal. Broken contours represent structure based on incomplete data. See Figure 4 for cross sections along lines *A–B* and *C–D*. (By A. H. Bell, *Illinois Geol. Survey, Illinois Petroleum*, No. 10 [July 23, 1927], pp. 6–7.)

1. Odin Coal Company's mine.
2. Chicago and Sandoval Coal Company's No. 1.
3. Chicago and Sandoval Coal Company's No. 2.
4. Marion County Coal Company's Glen Ridge.
5. Centralia Coal Company's No. 4.
6. Centralia Coal Company's No. 3.
7. Centralia Coal Company's No. 1.
8. Centralia Coal Company's No. 2.
9. Centralia Coal Company's No. 5.

The logs for the wells drilled by the Southwestern Oil and Gas Company, which owns nearly two-thirds of the productive leases in the Sandoval field, are "skeleton" logs, and most of them give the depth of only a coal and the Benoist sand. The coal recorded in some of them is probably Herrin (No. 6) coal. In determining the structure of the Benoist sand the skeleton logs could be used with very few exceptions, but many of them could not be used in constructing the structure map of the coal bed because of difficulty in correlating the coals. Accordingly the structure of

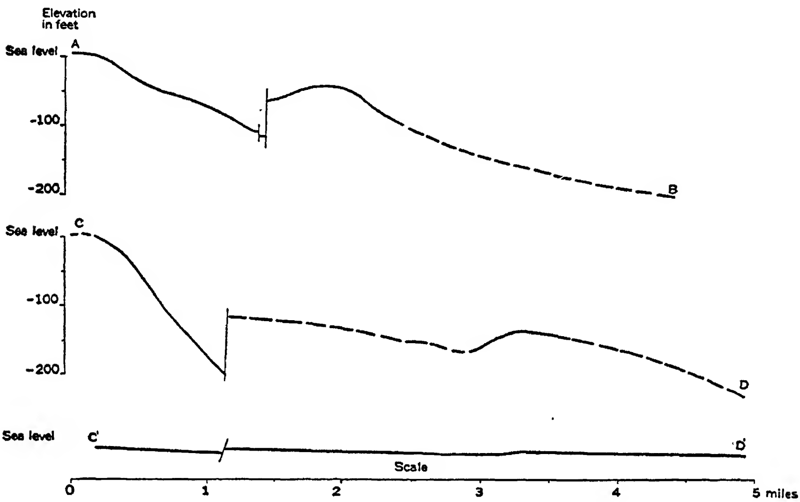


FIG. 4.—*A–B*, cross section through Glen Ridge anticline and Junction City dome. *C–D*, cross section through Hanseman well and Langewisch-Kuester pool. *C′–D′*, same cross section as *C–D*, with vertical and horizontal scales equal. See Figure 3 for lines of cross sections. (From *Illinois Geol. Survey, Illinois Petroleum*, No. 10 [July 23, 1927], p. 4.)

the coal was determined from a smaller number of datum points than that of the sand.

Two cross sections through the Sandoval pool (Fig. 7) compare the attitude of No. 6 coal with that of the top of the Benoist sand. They show an increase of interval of 30 feet toward the west and north.

PRODUCING HORIZONS

In order to consider the relation of production to structure, a brief résumé of the producing sands is here given; and for the purpose of showing their relative importance, some production figures are included. Oil

has been produced from five sands in the Centralia-Sandoval area, three of which are in the Pennsylvanian and two in the Chester. Named in order from the top downward, these are the (1) Dykstra, (2) Wilson, (3) Petro,

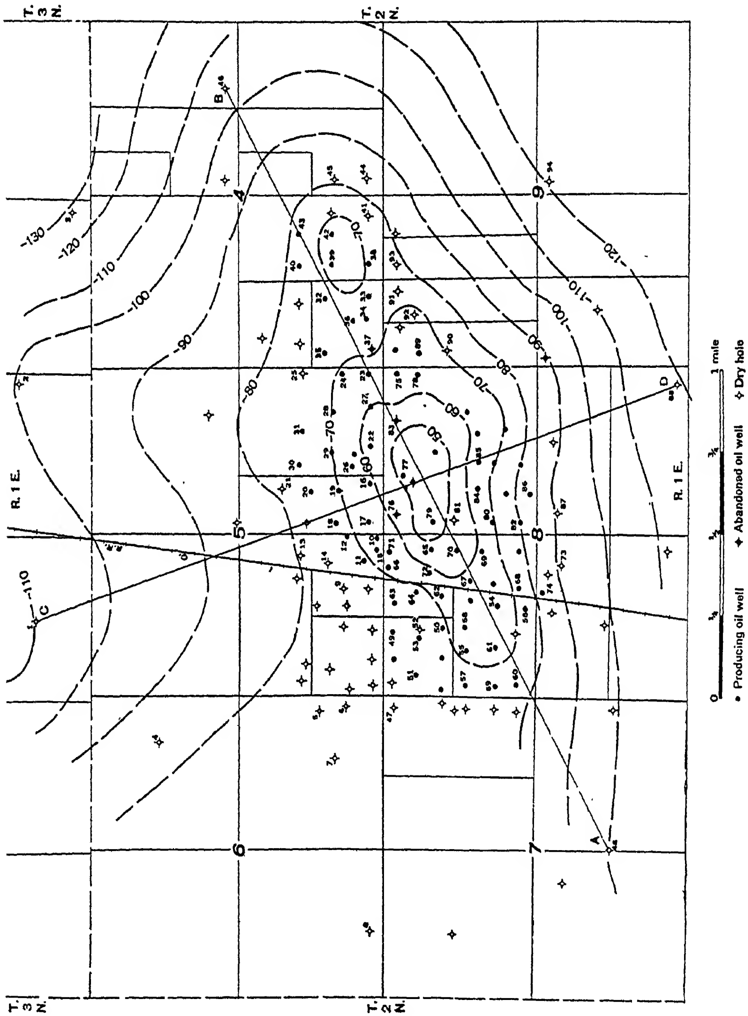


FIG. 5.—Structure map of Sandoval pool, Marion County, Illinois. Key horizon, top of Herrin (No. 6) coal. See Figure 7 for cross sections along lines *A–B* and *C–D*. (By A. H. Bell, *Illinois Geol. Survey, Illinois Petroleum*, No. 10 [July 23, 1927], p. 5.)

(4) Stein, and (5) Benoist sands. Although no locality is known in which they are all present, their approximate stratigraphic positions are illustrated in one generalized section (Fig. 8).

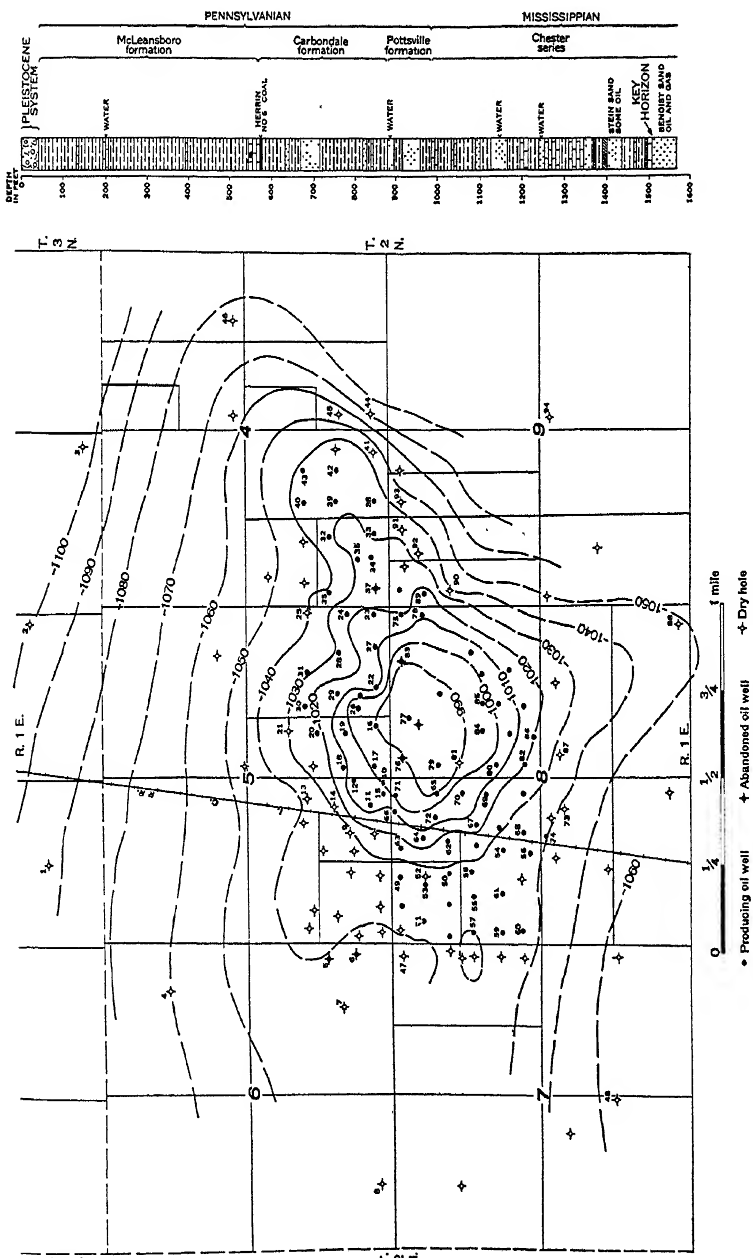


FIG. 6.—Structure and typical log of Sandoval pool, Marion County, Illinois. Key horizon, top of Benoist sand. (By A. H. Bell, *Illinois Geol. Survey, Illinois Petroleum*, No. 10 [July 23, 1927], p. 8.)

Pennsylvanian sands.—The Dykstra sand, lying closely below Herrin (No. 6) coal, is the sand in which oil was discovered in the area. The total production obtained from it has been insignificant. It is one of the two producing sands in the Junction City pool; the other is the Wilson sand,

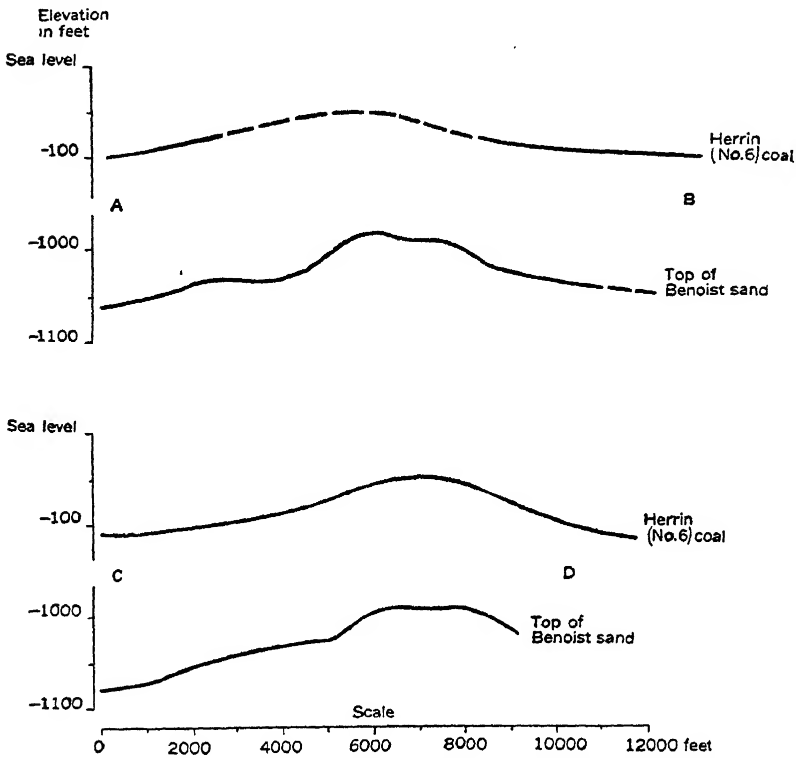


FIG. 7.—Cross sections through the Sandoval pool, comparing the altitude of Herrin (No. 6) coal with that of the top of the Benoist sand. See Figure 5 for lines of cross sections. (From A. H. Bell, *Illinois Geol. Survey, Illinois Petroleum*, No. 10 [July 23, 1927], p. 9.)

which is situated about 100 feet lower in the section. In the summer of 1926, 6.6 barrels per day were being produced by nine pumping wells from the Wilson sand and 2.5 barrels per day by two pumping wells from the Dykstra sand.

The most important Pennsylvanian production in the area is that of the Wamac pool, where the oil comes from the Petro sand which has been placed tentatively in the Pottsville, although it may belong in the lower

part of the Carbondale. This field was opened early in 1922. During the period of five years from the beginning of 1922 to the end of 1926, approximately 200,000 barrels of oil was produced.

Chester sands.—The Benoist sand has produced nearly all of the 2,500,000 barrels of oil obtained from the Sandoval pool. It extends from 930 to 980 feet below the Herrin (No. 6) coal. Approximately 100 feet above the Benoist sand in the section is the Stein sand from which the first oil at Sandoval was produced. The Stein-sand production was relatively small and short-lived as compared with that from the Benoist sand, and all the oil now produced in the field is from the Benoist sand. The producing sand in the Langewisch-Kuester and Brown pools is in the lower Chester, which has been tentatively correlated with the Stein sand of the Sandoval pool. This production, although small, has proved to be long-lived.

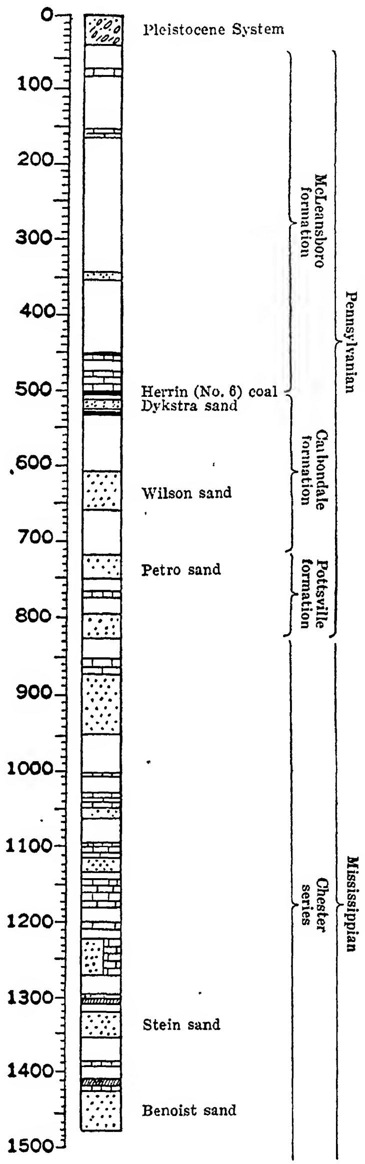


FIG. 8.—Generalized columnar section of Centralia-Sandoval area. Depth in feet.

RELATION OF PRODUCTION TO STRUCTURE

The productive areas are so situated with respect to the structural features of No. 6 coal as to suggest the probability of the accumulation of the oil into pools under two sets of geological conditions. In the Sandoval and Wamac pools, production extends over the tops of domes; and the boundaries of production tend to be parallel with the structure contours.

The location of these pools seems to have been determined by the folding of porous sand strata of relatively wide lateral extent. On the other hand, the minor pools, Junction City, Langewisch-Kuester, and Brown, are situated on the flanks of anticlines; and the determining condition in their location seems to have been the occurrence of localized bodies of porous sand which were features of original deposition.

Martinsville Pool, Illinois

By Gail F. Moulton

INTRODUCTION

The Martinsville field is in the northern part of the southeastern Illinois oil fields in Clark County, as shown in Figure 1. Production in the area was first developed from the Pennsylvanian sand and the top of the Mississippian limestone at shallow depths, during the period of great activity following the discovery of oil in Clark County in 1905. Deeper drilling in 1910 a few miles away in the Westfield pool resulted in the discovery of production in the Trenton limestone from a depth of approximately 2,400 feet. Adverse market conditions and the small size of the well prevented further interest in drilling to this deeper "pay" until 1919, when a better well was obtained. Within a short time several other deep wells were drilled. At this time, in order to assist the operators in more intelligent prospecting, the Illinois Geological Survey issued outline reports on geological conditions and recommended deep drilling in certain favorable areas.[1] The 1920 *Press Bulletin*, particularly, outlined areas worthy of deeper drilling. The Martinsville deep production was discovered by drilling in one of these areas.

The first deep test drilled in the Martinsville pool was planned as a test of the Trenton, and was the Trenton Rock Oil and Gas Company's John Carper No. 1, as indicated on the accompanying map (Fig. 9). While drilling in a hole full of water from the "Mississippi lime" at approximately 1,250 feet, a strong showing of oil was found in a sand in the Kinderhook shale of Mississippian age at approximately 1,350 feet, or more than 1,000 feet above the proposed depth of the well. The well was completed with an initial production of 150 barrels after a shot, and de-

[1] L. A. Mylius, *Illinois State Geol. Survey Press Bulletins* (October, 1919, and July, 1920).

Frank DeWolf and L. A. Mylius, "A New Trenton Field in Illinois," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 4, No. 1 (1920), pp. 43–46.

clined to 25 barrels in a week, but was producing approximately 20 barrels a day at the end of six months.[1]

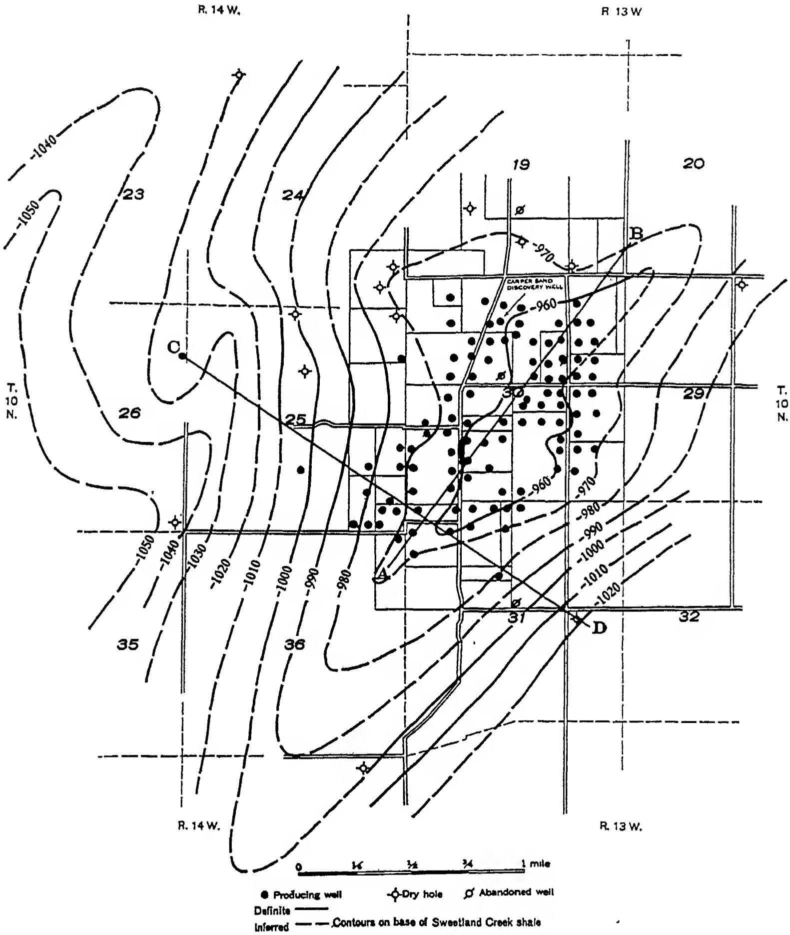


FIG. 9.—Subsurface structure of Martinsville pool, contoured on base of Sweetland Creek shale.

After the discovery of this more shallow commercial production in 1922, exploitation was carried on rapidly. In 1925 a well drilled deeper in search of other possible producing horizons found oil in a porous

[1] L. A. Mylius, "Oil and Gas in Eastern Illinois," *Illinois State Geol. Survey Bull.* 44–C (1923), footnote, p. 39.

weathered zone in the top of the Devonian limestone at a depth of approximately 1,550 feet. At this time the practice was established of drilling at the same time the Carper sand at approximately 1,350 feet and the "Niagaran" at 1,550 feet, using one string of casing to shut out the upper water and setting a perforated liner on a shoulder at the top of the Devonian limestone to exclude possible cavings. Most of the wells producing from the Carper sand were deepened by the end of 1926 and produced oil from both "pays."

STRATIGRAPHY

A typical stratigraphic section of the Martinsville pool shows that the surface rocks are Pennsylvanian in age and are composed largely of shales with sandstone beds in the lower part from which oil production is obtained.

The Pennsylvanian strata lie unconformably on limestones of lower Mississippian age. Additional production is obtained from the upper weathered part of this limestone series in part of the Martinsville pool. Lower Mississippian shales, thought to be of Kinderhook age, underlie the limestones; and it is in this shale series that the Carper sand occurs.

The Devonian limestone, or "Niagaran" of the drillers, lies unconformably beneath the Kinderhook shales. Of the "Niagaran," the upper 30 or 40 feet is the producing zone. Lower parts of the Devonian have been drilled but little in the area; nevertheless, it does not seem probable that other producing horizons will be discovered above the "Trenton" limestone.

Producing beds.—The basal Pennsylvanian sands are lenticular and owe their porosity to original conditions of deposition.

The lower Mississippian limestone has been considerably weathered and owes its porosity largely to secondary processes during the post-Mississippian period of erosion.

The Carper sand is a very fine-grained sandstone which was deposited irregularly during a time of general shale deposition, and the sand was probably deposited by mild off-shore currents. Commonly two or more beds of the sandstone are reported in drill records, with 10–15 feet of dark shale between them. In a few wells as many as four beds of sandstone are reported in the Carper zone. Ordinarily the top sand is barren of oil, although in a very few wells it has produced. The second sand lens is generally the principal producing member of the Carper group. The oil in the Carper sand is accompanied by a notable amount of gas under pressure; but because of the low permeability of the sand, production is generally small.

The "Niagaran" is a porous weathered zone, in the upper part of the Devonian-Silurian limestone series, which is cavernous on a small scale because of the solvent action of percolating waters during the post-Devonian time of erosion. It is characterized by a greater uniformity of porosity than is the Carper sand and is a dependable zone, for no test drilled deep enough in the area has failed to find it porous.

STRUCTURE

As shown on the general map of the Illinois-Indiana region, the Martinsville pool is situated high on the gently-dipping east flank of the La Salle anticlinal fold. Although the anticline is clearly a structural feature of the region, as shown by the contours based on the Pennsylvanian coal (Fig. 1), the structure shown in the Pennsylvanian strata seems to be principally the result of renewed deformation in post-Pennsylvanian time in areas subjected to important pre-Pennsylvanian folding. Detailed studies[1] in large areas in Clark County and the counties north have shown that in much of the territory on the high part of the La Salle anticline a notable relief had been developed on the surface on which the basal Pennsylvanian was deposited, and that in many places the local erosional elevations correspond with areas of local structural uplift. The principal uplift of the Martinsville region has a trend slightly west of north, but the local fold on which the deep production is found has a northeast trend and makes an angle of about 40° with the trend of the regional uplift.

The structure maps accompanying this report show contours drawn on the top of the Casey sand of the Pennsylvanian, the top of the Mississippian limestone, and the base of the Sweetland Creek shale of the Devonian.[2] In comparing the structure shown on the horizons contoured, full cognizance should be taken of the relative abundance of data as shown by the well locations on the maps, for well records represent the only source of information. Further, the records of the older shallow wells are generally very meager, making correlations difficult. The records of the deeper wells below the Mississippian lime are generally detailed and accurate.

The contours drawn on top of the Casey sand of the Pennsylvanian (Fig. 10) show a slight suggestion of an anticlinal nose in the Martinsville

[1] L. A. Mylius, "Oil and Gas Development and Possibilities in Parts of Eastern Illinois," *Illinois State Geol. Survey Bull. 44-C* (1923).

[2] L. A. Mylius, maps of Casey sand and top "Mississippi lime" from bulletin now in press; Gail F. Moulton, maps of structure of base of Sweetland Creek shale from *Illinois State Geol. Survey, Illinois Petroleum No. 4* (1926).

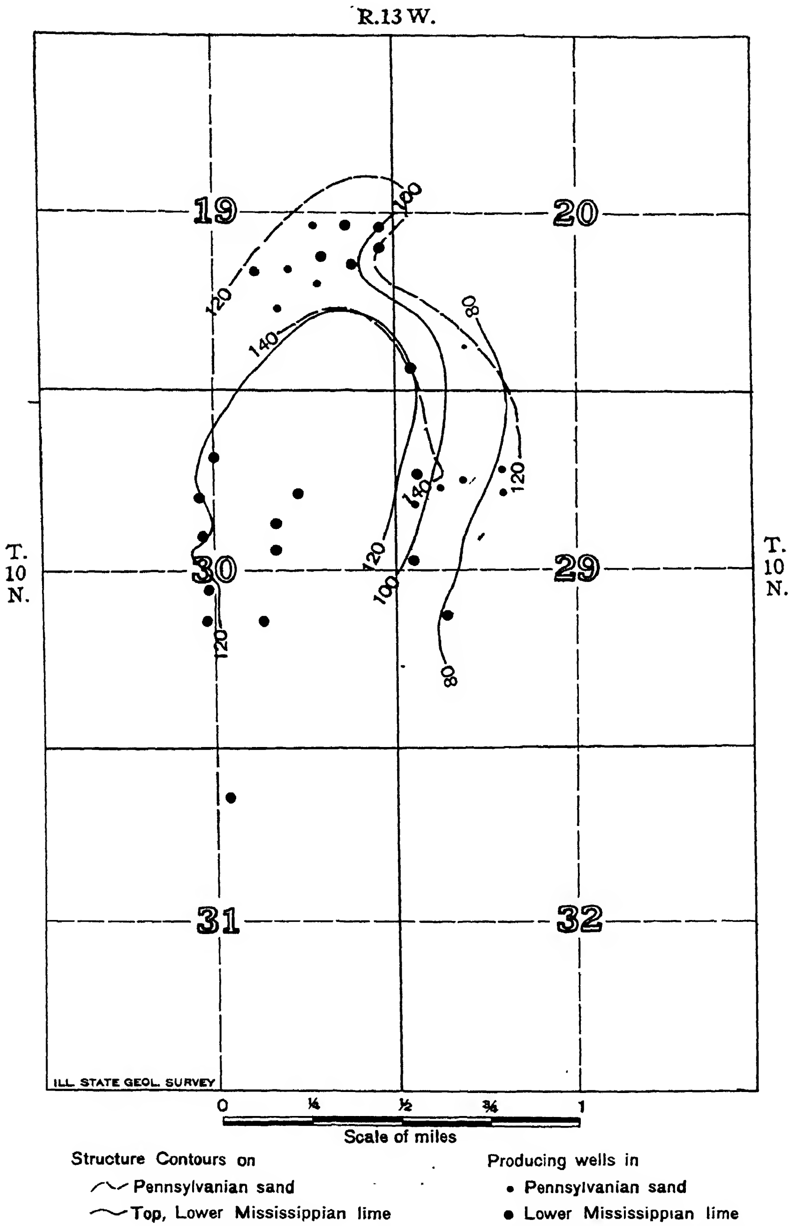


FIG. 10.—Subsurface structure of Martinsville pool on shallow producing beds. (Map by L. A. Mylius, *Illinois Geol. Survey Bull. 54* [1928], Plate 29.)

area. The contours showing the elevation of the surface of the Mississippian limestone more plainly indicate a dome. Each of these structures seems to have a north-south trend which is essentially parallel with the regional folding. The structure of the base of the Sweetland Creek shale shown on the map (Fig. 9) is a rather pronounced anticline with a northeast-southwest trend and a somewhat steeper dip on the southeast flank than on the northwest.

The relation of these structures strongly suggests that the principal local folding which caused the accumulation in the Carper sand and the "Niagaran" took place in pre-Pennsylvanian time. There are no data available to show whether there was appreciable warping after the close of the Devonian and before the deposition of the overlying shale, but the variation in the thickness of this shale in an Indiana area is strongly suggestive of such warping. The Carper sand in the Martinsville pool is so irregular, as shown in the cross sections (Fig. 11), that results of an attempt to determine whether the intervals between the sand and the top of the Devonian lime were constant would be of doubtful significance.

Evidently the cross fold on which the Martinsville deep production has accumulated represents the result of horizontal movement along the axis of the La Salle anticline in conjunction with compressional forces acting normal to it, so that a rotational strain was set up with the axis of elongation trending northeast. In other words, the earth mass east of the La Salle fold had a north component of motion relative to that west of the La Salle fold.

If Chester sedimentation once extended north into Clark County, as it probably did, the streams during the post-Chester and pre-Pennsylvanian erosion were cutting through a series of alternately hard and soft beds underlain by a somewhat thick series of resistant limestones. Normally, the erosion of such a series of reasonably uniform resistant beds, like the Mississippian limestones of the area, would result in rather close correspondence between topographic elevations and structural elevations, provided erosion did not completely remove the limestones from parts of the area. Accordingly, it is concluded that the pre-Pennsylvanian folding was a very important factor in determining the location of production from the top of weathered Mississippian limestone, for most of it comes from local erosional elevations on the general uplift.

There is no conclusive evidence as to the origin of the Pennsylvanian structure in this area, except that there was general folding along the La Salle anticline in post-Pennsylvanian time. The data do not show whether the small local domes in the Pennsylvanian are generally related to folds

in the underlying beds or not. There is some possibility that differential compacting over some of the topographic elevations, developed on the pre-Pennsylvanian surface, combined with longer continued sand deposition in some such places, resulted in the local irregularities in the Penn-

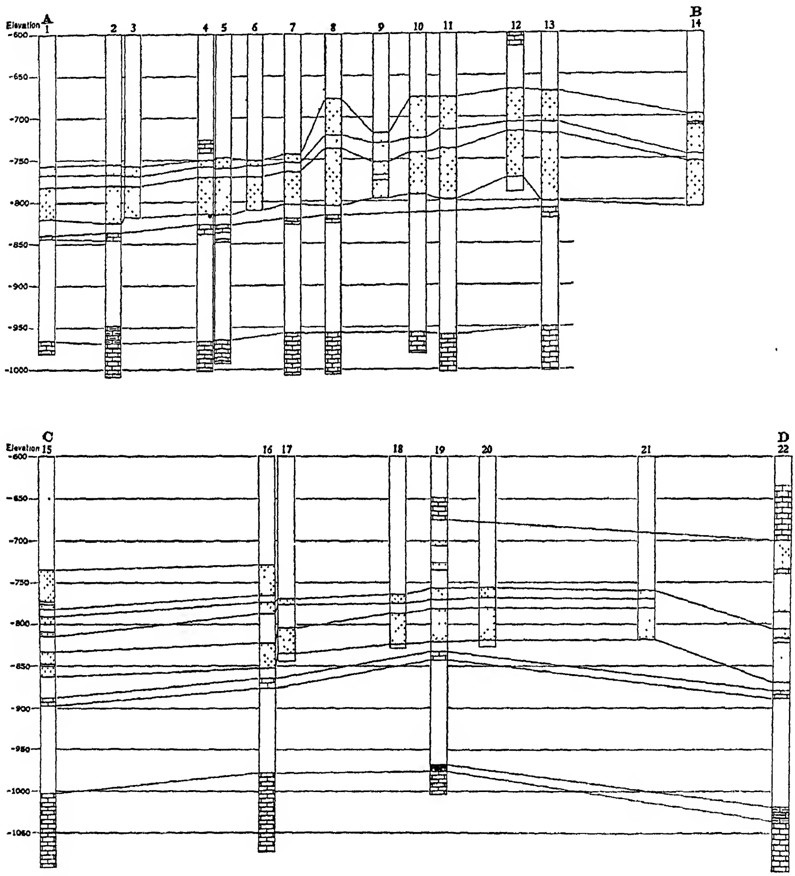


FIG. 11.—Structural cross sections of Martinsville pool (Fig. 9), showing irregular sand conditions of the Carper (middle of section) and position of the "Niagaran" (bottom of section).

sylvanian structure. There is the additional possibility that in the post-Pennsylvanian compression, which caused a further depression of the coal basin west of the La Salle anticline, the active forces were transmitted to the incompetent Pennsylvanian strata largely through the more com-

petent underlying Mississippian limestone. Accordingly, those parts of the limestone which projected up into the Pennsylvanian series should have acted somewhat as buffers and caused local disturbances. This hypothesis is offered as an alternative explanation for the occurrence of the slight Pennsylvanian fold over the erosional elevation in the Mississippian limestone.

RELATION OF PRODUCTION TO STRUCTURE

The production from the Pennsylvanian sand seems to be influenced to a considerable extent by the structure, but variation in porosity of the sand was undoubtedly a very important factor in determining where oil would accumulate. The dips in the Pennsylvanian are so gentle that it is difficult to determine whether the structure was as important a factor as sand conditions in causing oil accumulation.

The accumulation of oil in the Mississippian limestone was determined largely by the presence of elevations in the erosional surface on which the Pennsylvanian was deposited. The rate and amount of production from the limestone are dependent on the development of porosity and on the permeability of the limestone—conditions produced by weathering processes in pre-Pennsylvanian time.

As the Carper sand is lenticular in character, production from it is determined by a combination of the primary structure, due to conditions of deposition, and the secondary structure which resulted from folding. For that reason the production is not found on the highest parts of all the folds, but rather in the higher part of each separate porous sand body, whether it be near the crest or some distance down a flank of the fold. The irregularity of the Carper sand also causes large variation in the productivity of the wells.

The structural control of production from the "pay" at the top of the Devonian limestone is very marked, for this permeable zone is essentially continuous. Wells drilled on the high part of the structure find the "pay" to be oil-saturated through a considerable thickness and to produce a large amount of oil with but little water. The wells located a short distance down the flank find less of the oil-saturated "pay" and produce a much larger amount of water. At the edge of the producing part of the structure there is a slight showing of oil immediately before the wells are drilled into water. As far as present development has shown, the division between producing and non-producing territory in this "pay" is parallel with a structural contour enclosing the field.

FRANCISCO POOL, GIBSON COUNTY, INDIANA[1]

By Gail F. Moulton

INTRODUCTION

The Francisco pool, in Sections 13 and 24, Center Township, Gibson County, as shown on the regional map, was discovered in 1922 by a well drilled by Mann, Huber, and Tichenor of Evansville, Indiana. During the next two years seventeen wells were drilled, eight of which produced oil. Four of the nine failures had good showings but were shot and flooded by bottom water and could not be repaired.

From 1924 to 1926 there was no further development in the field. Late in 1926, Mann and Huber drilled a well[2] a short distance south of the center of the SE. ¼ of Sec. 13, and found good production. Seven more producing wells and five dry holes have been drilled since that time, and at the close of 1927 development has stopped. The production of this field, principally obtained from eight wells, is approximately 300 barrels per day, or about 10 per cent of the total for the state of Indiana.

The only published report on the geology of the Francisco pool is included in a general report on the southwestern Indiana fields of the Indiana Geological Survey.[3] According to Logan the production in this field is obtained from the Sample sand of lower Chester (upper Mississippian) age. Subsequent developments have led to the discovery of gas in a shallow Pennsylvanian sand at a depth of 400 feet, which is of great value to the operators, for there is practically no gas produced with the oil and there was need of fuel for operating the pumping power. The oil has a gravity of approximately 27° A.P.I. and did not give very satisfactory results with the equipment installed.

STRATIGRAPHY

The typical rock section of the Francisco pool is shown in the graphic well log accompanying the structure map (Fig. 12). The surface rocks are of Pennsylvanian age and are composed largely of shales in the upper part and an important basal sandstone. Coal beds and limestone beds form a minor part of the Pennsylvanian. Of the coals, a bed at a depth of approximately 225 feet (Indiana coal No. 5), is of considerable commercial importance.

The Chester series of upper Mississippian age underlies the Pennsylvanian formations and is composed principally of shale, but contains im-

[1] Presented through the courtesy of Mann and Huber, Evansville, Indiana.

[2] Private report by the writer.

[3] W. N. Logan, "Geological Conditions in the Oil Fields of Southwestern Indiana," *Indiana Dept. of Conservation Publication No. 42*, pp. 48–55.

portant beds of limestone and sandstone. The producing sand lies approximately 300 feet below the top of the Chester at a depth of approximately 1,400 feet. Some of the wells have penetrated the Chester strata below the producing sand, but none of them in this area has been drilled into the thick limestones of the lower Mississippian.

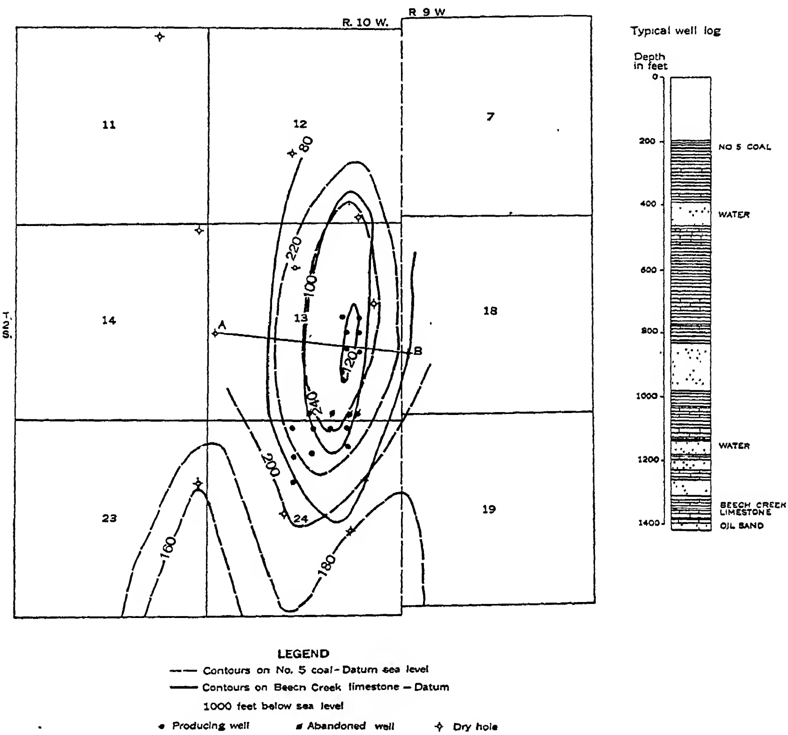


FIG. 12.—Subsurface structure of Francisco pool, contoured on Indiana No. 5 coal and on Beech Creek limestone.

As the lower formations have not been tested on this structure, the probability that they will be found productive cannot be estimated. In view of the established productivity of some of these beds in pools near by, it is believed that drilling to test them on the highest part of the structure is justified.

Producing sand.—The producing sand, which is correlated as the Sample formation by the Indiana Survey,[1] is fairly well sorted and is com-

[1] W. N. Logan, *op. cit.*, p. 49.

posed of subangular to angular grains with an average diameter of 0.3 mm. The upper part of the sand is somewhat lenticular and in some parts of the area becomes shaly. Cores taken from the well near the center of the SE. $\frac{1}{4}$ of Sec. 13 with a cable-tool core bit provided by the courtesy of the Keystone Driller Company showed that the sand was rather uniform in porosity, having a connected, oil-saturated porosity of 17 per cent. The porosity of this sand is primary.

The lower part of the sand seems to be more permeable than the upper part and to be saturated with water in all parts of this structure. It is believed that at least the lower 10 feet of the sand is water-bearing, even on the highest part of the structure.

STRUCTURE

Regional structure.—As shown on the general map of the Illinois-Indiana region (Fig. 1), the Francisco pool is on the west-dipping monocline on the west side of the Cincinnati arch, which is east of the area of this map. The generalized contours on the coal do not show the presence of any fold at this place, for the structural irregularities are too local to be indicated on such a small-scale map.

Local structure.—The detailed map of the Francisco pool (Fig. 12) shows the structure of the Indiana No. 5 coal by means of dotted contours. Most of the data giving the coal structure were obtained from coal tests, for the oil operators, fearing damage suits from coal operators, make a practice of reporting only dark shale at the horizon of the No. 5 coal, and record presence of coal only rarely. The coal data indicate the presence of a rather well-defined fold in the area which is now productive.

The heavy contours are drawn to show the structure of the Chester beds (Fig. 12) and are based on elevations of the base of the Beech Creek limestone above a datum plane 1,000 feet below sea-level. These contours indicate the presence of a dome having an east dip of more than 40 feet in a quarter of a mile, and a closure of 40 feet. The dome is elongate approximately north and south. It is mapped for 2 miles along its axis.

The structure of the Pennsylvanian here, as in most of the oil pools in southwestern Indiana, is similar in its general features to the structure of the Chester series below. As might be expected, a pronounced Pennsylvanian fold, like the one on which the Francisco pool has been developed, bears a close resemblance to the Chester structure below, except in minute details. Drilling on the basis of coal structure in this locality probably would have resulted in the discovery of the best part of this pool by the first well drilled.

The best wells have been obtained on the highest part of the structure. Except for the irregularities in the top of the sand, as shown in the cross section (Fig. 13) along an east-west line through the central part of Section 13, the accumulation of oil in this field is governed by structural

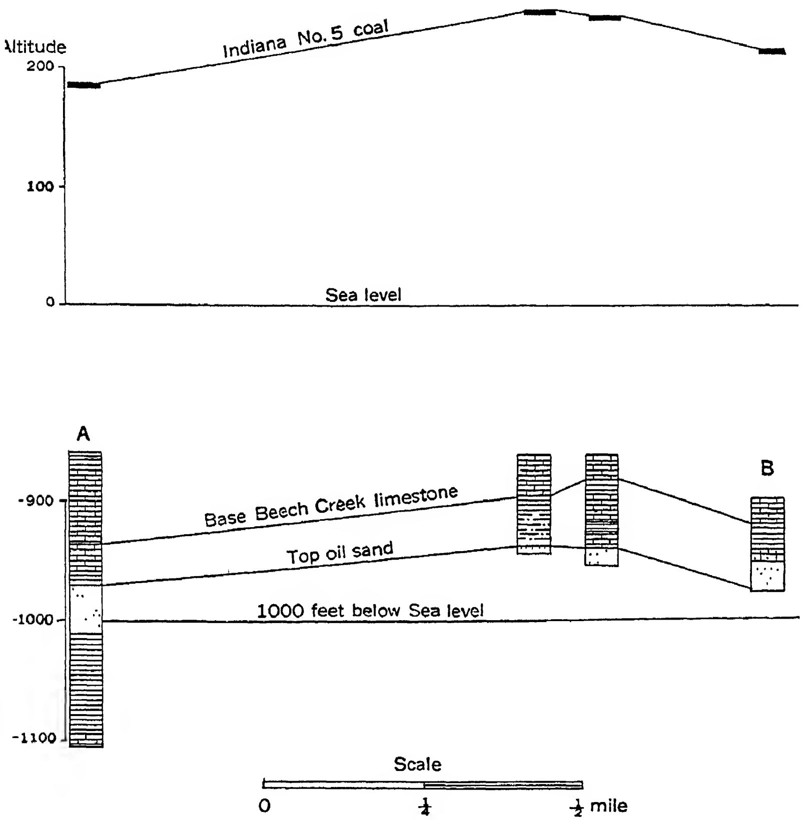


FIG. 13.—Cross section A–B through Francisco pool (Fig. 12). Depths in feet.

conditions in accordance with the anticlinal theory. The wells on the south end of the structure, however, are producing from thin beds of sand which occur above the main body of oil sand. To take the irregularities in the sand into consideration, a contour map showing the elevation of the top of the sand might be prepared. The boundary of production would be found parallel with contours on the sand surface.

VIRGIL POOL, GREENWOOD COUNTY, KANSAS[1]

A. L. BEEKLY[2]
Tulsa, Oklahoma

ABSTRACT

The Virgil pool is one of the early pools to produce from the "Mississippi lime" in Kansas. Since 1916 the pool is estimated to have produced 5,000,000 barrels of 37°–41° Bé. gravity crude from small long-lived wells located in an area of more than 1,000 acres. The pool is on a well-defined closed anticline which has been the governing factor in the accumulation of the oil.

INTRODUCTION

The Virgil pool is one of the older "First-break" pools in Kansas. It is best known as a pool of small wells of exceptional staying qualities and as a structural accumulation in which the distribution of paying production on the structure is irregular to the point of being streaked.

Acknowledgments are made to the Mid-Continent Petroleum Corporation for permission to publish the maps and data contained in this paper; to L. J. Youngs, who mapped the surface structure and offered valuable suggestions; and to B. R. Mills, who did the drafting on maps and sections. The writer is also indebted to John L. Rich for determination of the Lansing-Kansas City division lines as shown in Figures 3 and 4.

LOCATION

The Virgil pool proper centers about Sec. 14, T. 24 S., R. 12 E., in northeastern Greenwood County. This section is approximately 3 miles southwest from the town of Virgil on the Chanute-to-Emporia branch of the Santa Fe Railroad. The Virgil structure lies mainly in the eastern half of the township, but for present purposes the township is mapped complete.

PRODUCTION

On October 12, 1916, the Cosden Oil and Gas Company completed the discovery well of the Virgil pool. This well, Wayham No. 1, in the southeast corner of Section 14, made 15 barrels, initial production. Since

[1] Manuscript received by the editor, November 26, 1928. Presented by title before the Association at the Tulsa meeting, March 26, 1927.

[2] Chief geologist, Mid-Continent Petroleum Corporation.

this beginning, 230 wells have been drilled, of which approximately 193 were oil producers, 10 were gas wells, and the remainder dry holes. The scattered productive areas have been very closely drilled, with an average of 1 well to 5 acres, so that the total oil-producing wells represent slightly less than 1,000 productive acres. Although production figures on the entire field are not available, the productivity of the pool is indicated with some degree of accuracy by the history of 34 producing wells on which figures are available. The average initial production of these wells was 28.5 barrels per day; and up to and including May, 1928, they had produced 947,377 barrels, or an average acre yield of 5,573 barrels. These wells produced nearly 3,000 barrels in the month of May, 1928. The ultimate recovery from the acreage represented will, in all probability, exceed 6,000 barrels per acre.

PRODUCING HORIZONS

Three wells in Sections 6 and 7 and 4 or 5 wells in Section 36 have produced from a sand in the lower part of the Cherokee, which is at, or near, the horizon of the Bartlesville sand. In most of the township this sand is absent or represented only by a sandy shale streak which has yielded showings of oil and gas in many places but no commercial production other than that already mentioned. Practically all of the important oil production of the Virgil pool comes from the so-called "First break," which is a porous zone at, or very near, the top of the "Mississippi lime." In the northeast corner of the SW. ¼ of Sec. 23 a well which penetrated the "First break" from 1,694 to 1,719 feet, continued through "Mississippi lime" to 2,071 feet, through shale to 2,124 feet, and got a hole full of water in sand from 2,124 to 2,134 feet. Only two other pre-Mississippian tests have been drilled in the township, one in the northeast corner of the SW. ¼ of Sec. 31, and the other in the southeast corner of Sec. 32. These holes also filled with water from the deep sand. No samples of the deep formations penetrated in these three wells are available for study; but in view of the fact that the three logs are closely correlated as to thickness and character of the "Mississippi lime" and the 60 feet of underlying black shale, this shale is believed to be Chattanooga, and the sand upon which it rests, the Ordovician Mounds ("Wilcox") of Oklahoma.

STRATIGRAPHY

The conspicuous outcropping beds of the township in which the Virgil pool is located are the Topeka, Deer Creek, and LeCompton limestones of the Shawnee group of the Pennsylvanian. The Deer Creek is separated from the Topeka above by the Calhoun shale approximately 40 feet in

thickness, and from the LeCompton below by approximately 60 feet of Tecumseh shale. The limestone outcrops are shown on the areal and surface structure map (Fig. 1), and the stratigraphic column downward

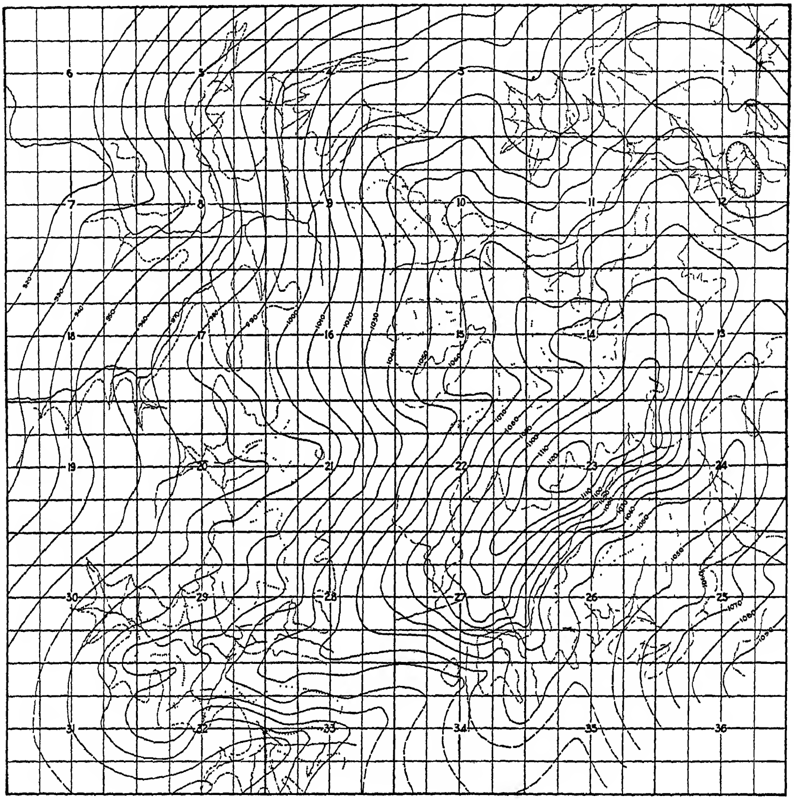


FIG. 1.—Limestone outcrops and surface structure, Virgil pool, Greenwood County, Kansas. Datum, Lecompton limestone. Contour interval, 10 feet. The area mapped is T. 24 S., R 12 E., 6 miles square.

Topeka limestone - - - -
Deer Creek limestone · · · · ·
Lecompton limestone – ·· — ··

into the top of the "Mississippi lime" is shown in the cross sections *A-A* and *B-B*, Figures 3 and 4. The lower 200–300 feet of the Shawnee is present; and below it are the several groups with approximate thicknesses as follows: Douglas, 400; Lansing, 260; Kansas City, 200; Marmaton, 300; and Cherokee, 250 feet. Each of the three deep wells in Sections 23,

31, and 32 which penetrated formations below the "Mississippi lime" showed approximately 350 feet of "Mississippi lime," then 50–70 feet of black shale, and stopped in water sand which, in Section 23, is in contact with the black shale and in the other two wells is separated from it by a thin gray lime. The black shale is correlated with the Chattanooga, and the water sand is believed to be Upper Ordovician, probably the Mounds sand ("Wilcox") of Oklahoma. It should be borne in mind that the Virgil pool was mainly developed before the value of formation samples was appreciated and before the saving of them became general practice. All subsurface correlations are therefore based on drillers' logs and such descriptive matter as is contained in them. On the accompanying cross sections, group division lines have been shown and a few of the better-known formation members have been named. Logs of wells in the district indicate a uniform thickness of "Mississippi lime." They show no evidence of angular unconformity; and although erosion of the lime top is evident, the Cherokee was probably deposited on an almost perfectly peneplaned Mississippian surface.

STRUCTURE

The Virgil pool is located on a surface structure having more than 60 feet of closure with its top in the west-central part of Section 23 and its long axis extending approximately from the center of Section 12 to the center of Section 27. Figure 1 shows the surface structure in detail as mapped on the top of the LeCompton limestone and on intervals between this datum bed and the Deer Creek and Topeka limestones, which also served as excellent markers. The subsurface structure shown by Figure 2 is contoured on the top of the "Mississippi lime." Although not recognized as a satisfactory marker in many localities in Kansas, it was used in this field for the reasons that it happens to conform very closely with the surface structure and also with that of the Lansing or Kansas City limes and that it is stratigraphically within a few feet of the principal oil-producing horizon. The 115 available well logs show such remarkable regularity of section and intervals that the subsurface structure as mapped on the top of the "Mississippi" cannot differ in any essential respect from that of any higher bed or that mapped at the surface.

ACCUMULATION AND SOURCE

Figure 2, showing the distribution of oil wells, gas wells, and dry holes on the subsurface structure, shows the areas of maximum accumulation, but it should not be inferred from this that the blank spaces on the

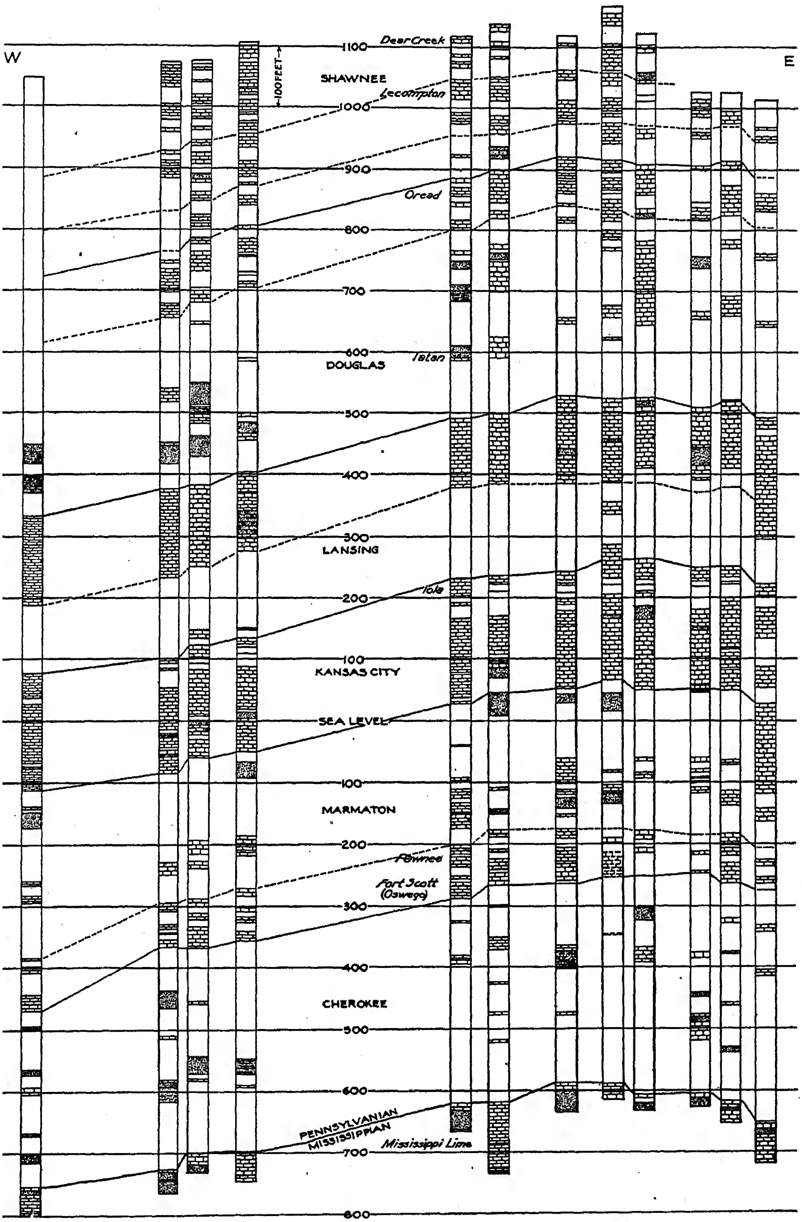


FIG. 3.—Cross section *A-A*, Virgil pool (Fig. 2).

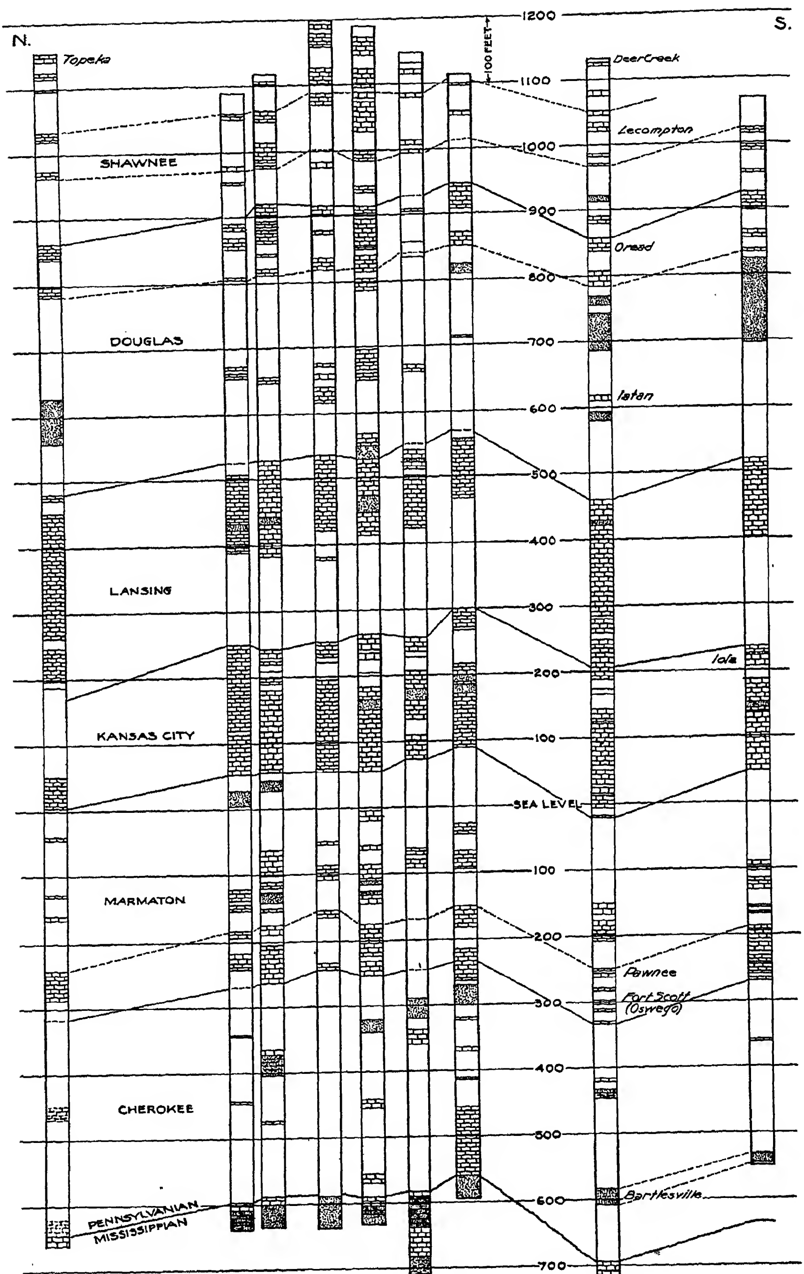


FIG. 4.—Cross section *B-B* Virgil pool (Fig. 2).

tration of oil in the pool. The deep well in Section 23 shows only water in the sand immediately below the Chattanooga—a condition that seems to preclude the possibility of upward movement of oil locally from the Ordovician, and leaves but one explanation for the accumulation, namely, movement of oil up the dip through the porous zone from which the oil is produced. This pay horizon, known to the drillers as the "top of the lime" or the "First break," is a porous zone in the lime, cherty in some localities but nowhere a true sand. The variable porosity of this zone accounts for the distribution of rich and lean producing areas on the anticline. Study of the well logs gives the impression that the porous pay streak is not a perfectly definite stratigraphic horizon but that it ranges slightly upward and downward within a restricted zone which as a unit is conformable with the lime beds below.

The Virgil pool is in the rank of the many which offer no conclusive evidence as to the origin of the oil. The facts available seem to leave an open question as to whether the source was local in the Cherokee shales with which the "pay" comes in contact in many places, or remote, with migration of the oil from great distances through the porous zone in which it was finally trapped. In support of the former, it is true that oil of almost identical character and gravity is found in isolated sand lenses at the Bartlesville horizon in the Cherokee, with no apparent media through which long-range migration could have taken place. It is equally true, however, that the "First break," or "Mississippi lime pay," is widespread in Kansas and Oklahoma; and, with few exceptions, penetration by the drill has encountered oil or water, indicating that the porous zone is sufficiently continuous to permit long-distance migration. This, coupled with the fact that the "Mississippi" has in some localities produced oil from structural traps in which no oil was found in the Bartlesville, favors the theory that at some distant point where conditions were favorable, lower Mississippian or pre-Mississippian oil moved upward through the section and migrated laterally through the porous "First break" to the structural traps from which it is produced.

MADISON SHOESTRING POOL, GREENWOOD COUNTY, KANSAS[1]

A. E. CHEYNEY[2]
Russell, Kansas

ABSTRACT

The Madison oil field is a part of one of the "shoestring" lines of production in Greenwood County, Kansas, which produce from Bartlesville sand lenses of great linear extent. The pattern and shape of the lenses, their double convex cross section, and their distribution with respect to paleogeography indicate that they represent sand bars and tidal delta bars formed by waves, currents, and tides near shore lines. Some of them may represent stream-channel deposits.

Structure as represented by surface beds, the base of the Kansas City formation, and the top of the "Mississippi lime" seem to conform but to be without definite relation to Bartlesville sand deposits except that these lenses occur between and on the sides of "Mississippi lime" buried hills, with the exception of the Seeley, Clark-Wick, and Shambaugh pools. Inasmuch as Bartlesville sand bodies are lenticular and are surrounded by shale which may have been the source rock, they are excellent oil reservoirs.

INTRODUCTION

The Madison pool, in the northeast part of T. 22 S., R. 11 E., Greenwood County, Kansas, on the main Sallyards-Thrall-Madison trend (Fig. 1), has been studied as a type because many of the wells in this pool were drilled entirely through the Bartlesville sand and most of the logs and elevations of the wells were already at hand.

The construction of the cross sections in the Madison pool was prompted by a desire to learn (1) the shape and origin of the Bartlesville sand deposits; (2) the relation, if any, between the sand deposits and the structure as represented by the surface beds, the Kansas City formation, and the top of the "Mississippi lime"; and, consequently, (3) the relation between structure and the accumulation of oil in the "shoestring" pools of the Greenwood County district.

ACKNOWLEDGMENTS

The writer is indebted to the Transcontinental Oil Company for permission to publish this discussion. Thanks are due to J. R. Eichelberger for assistance in drafting work and collecting data, to John L. Rich for criticisms and suggestions, and to R. F. McMillen for drafting work.

[1] Manuscript received by the editor, June 22, 1928.

[2] Geologist, Transcontinental Oil Company, Tulsa, Oklahoma.

DISTRIBUTION OF SHOESTRINGS

Sand lenses of relatively narrow width and great length are called "shoestrings." They are seldom noticed unless they are conspicuous features in the areal geology, as the Verden sandstone on the geological map of Oklahoma and the conspicuous lenses on the geological map of Missouri.

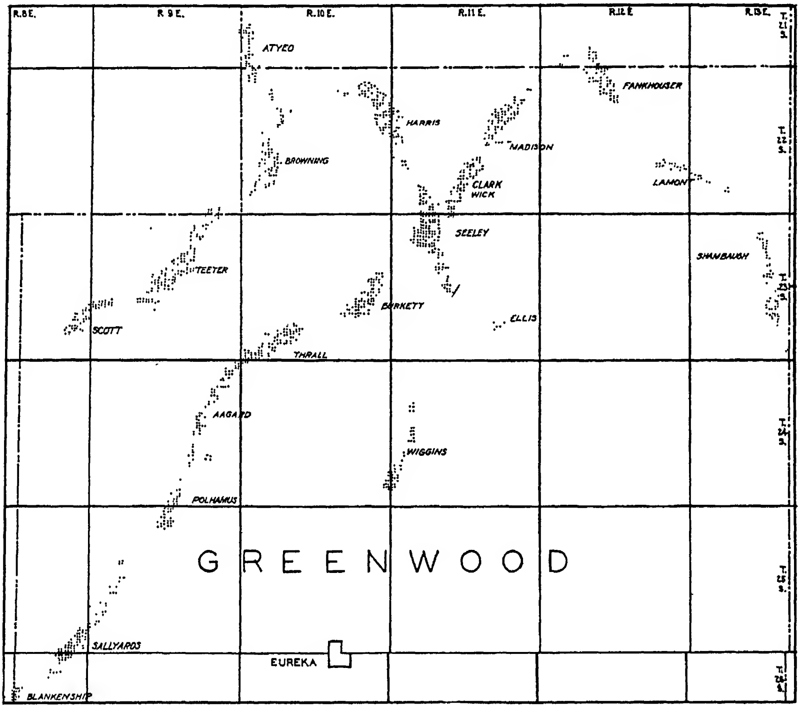


FIG. 1.—Oil pools in Sallyards-Madison trend, Greenwood County, Kansas. Width of area mapped, approximately 31 miles.

Oil developments have shown that they are numerous in eastern Kansas[1] and in Greenwood County, Kansas, as shown in Figure 1.

Discovery of shoestring production in Greenwood County was in the Sallyards and Teeter fields. Drilling in search for anticlinal production by means of wells located on noses mapped at the surface opened other fields which have been found to align in two major northeast-southwest trends and in several less clearly defined trends at right angles. The major

[1] John L. Rich, "Shoestring Sands of Eastern Kansas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), p. 103; Vol. 10 (1926), p. 568.

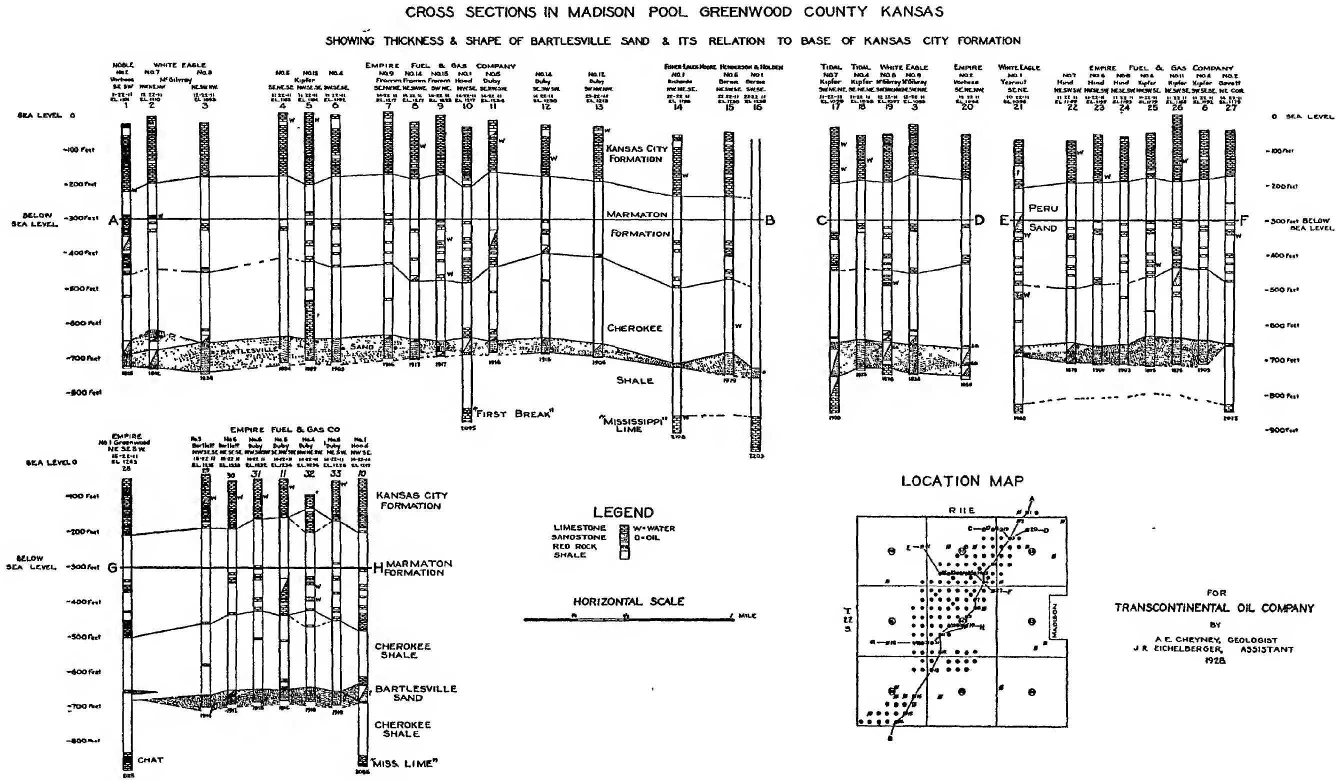


FIG. 2.—Cross sections in Madison pool, Greenwood County, Kansas.

shaped sand was found in section *E–F*, the greatest thickness being in log No. 25, with a gradual thinning toward the west and an abrupt thinning at the east end. The top of the sand in section *E–F* parallels the base of the Kansas City formation only in a general way, as log No. 21 is low, No. 25 is high, and No. 27 is relatively high on each horizon. The base of the sand slopes gradually eastward to log No. 6, where it rises abruptly. Section *E–F* is $1\frac{1}{2}$ miles long. In section *G–H* the top of the Bartlesville sand may be compared very well with the base of the Kansas City formation, if the sand in log No. 28 is considered as being above the regular Bartlesville horizon. In log No. 33 the Bartlesville is more than 41 feet thick, and thins toward the east in one location to 5 feet of sand and 45 feet of sandy shale, and gradually decreases in thickness toward the west. The shape of the base of the sand in section *G–H* is not clearly defined, since only the two end-wells penetrated the full extent of the sand. But it is quite probable that the other wells stopped very near the bottom of the sand, which would show a slight arching in the middle of the section, as in *A–B* and *C–D*. Section *G–H* is $1\frac{1}{4}$ miles long. It must be taken into consideration that the Bartlesville sand is a lenticular, irregularly shaped deposit, and cannot be expected to correspond very closely in detail with the dips of the Kansas City formation, which is rather uniform in thickness.

POSSIBLE ORIGIN OF BARTLESVILLE SAND BODIES IN THE MAIN TRENDS

The present Bartlesville oil pools are all in thick bodies of sand. It is well known that thin deposits of Bartlesville sand have been found outside the present producing trends, widely separated in the Greenwood County district, although many tests have shown the Bartlesville sand to be entirely absent. These widely-separated thin deposits of Bartlesville sand may be situated anywhere in the Bartlesville horizon, with reference to the thick sands of the producing pools, but as a rule are found in the upper part of the horizon or from 150 to 180 feet above the top of the "Mississippi lime."

In attempting to determine the origin of the Bartlesville sand bodies, it is important to consider their shape. In six of eight cross sections of the Teeter trend published by Cadman[1] the base of the sand is decidedly arched between the two ends of the sections, and the top of the sand is very uneven and hilly. Generally the high point on the top of the sand is directly over the high point on the base of the sand. Likewise, three of the

[1] W. K. Cadman, "The Golden Lanes of Greenwood County, Kansas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 1151–72.

four cross sections in the Madison pool show the base of the Bartlesville sand to be arched between the ends of the sections, and in one section the base of the sand curves downward between the ends of the section. The top of the sand is very irregular, and in only one section of the Madison pool is the high point on top of the sand directly over the high point on the base of the sand.

In considering stream-channel deposits, it is known that streams of old age meander and that streams of youthful age have deep channels with steep sides and no flood plain. The patterns of the producing trends (Fig. 1) do not seem to show meandering such as would be illustrated by stream channels of old age. Cross sections of the Bartlesville sands in the producing trends of the Teeter area and the Madison area do not show the shape of a deep channel with steep sides, or with a fairly level top and rounded or pointed bottom, as we would expect in fillings of youthful stream channels. In stream deposits we would expect the surface to be somewhat irregular, though nearly flat in general. It might be suggested that the Bartlesville sands may have been sand dunes in part, which would explain their irregular surface, but if that were true, the base of the sands should be more irregular than is shown, as illustrated by sand dunes along Arkansas River in Rice and Reno counties, Kansas.

It might be thought that the Bartlesville sands are parts of a large river delta, but this theory meets with some of the same objections as the stream-channel theory. Since the delta would have been farther from the source materials than the channel, it should have received finer materials.

The Bartlesville sands have a fine-to-coarse texture. Samples[1] which were analyzed were found to be practically the same as the sand from several wells in Oklahoma that were known to be true shore-line deposits.

Since the Bartlesville sands of the main trends were deposited in comparatively narrow strips ranging from $\frac{1}{4}$ mile to $1\frac{1}{2}$ miles wide, and in view of the preceding statements, we are led to believe that most of the Bartlesville deposits in the main trends belong to types of sand bars such as are now found off the coasts of New Jersey and the Carolinas. Some of the deposits may be due to tidal deltas. The writer has not studied each pool in detail, and undoubtedly different types of sand deposits are found in the different pools of the trends and cross trends. A few of the pools in the cross trends may be stream-channel fillings similar to some of the shoestring pools farther east in Kansas.

[1] From Transcontinental Oil Company's Jones No. 1 in SW. Cor., SE. $\frac{1}{4}$ of Sec. 30, T. 21 S., R. 10 E., Lyon County, Kansas. Analyzed by L. F. Athy in the Research Laboratories of the Marland Refining Company at Ponca City, Oklahoma.

RELATION OF THE SAND BODIES TO STRUCTURAL "HIGHS"

The normal dip of the surface beds in this area is northwest at a rate ranging from 20 to 30 feet per mile (Fig. 3). The Teeter-Pixlee trend is northeast and southwest in northwestern Greenwood County. The Sallyards-Thrall-Madison trend is northeast and southwest across north-central Greenwood County.

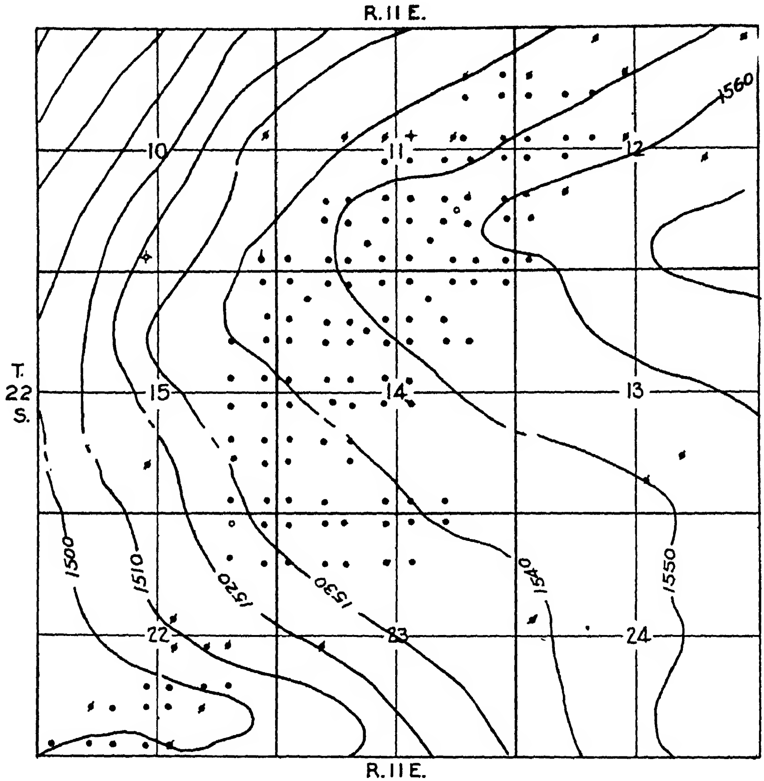


FIG. 3.—Surface structure of Madison pool. Contour interval, 10 feet. Width of area mapped, 3 miles.

The Teeter pool proper in T. 23 S., R. 9 E., is on the northwest flank of a large, pronounced surface dome. The top of the dome is a little more than a mile southeast of production. The trend continues northeast into what may be termed the "Green extension." Part of the Green extension lies along the west side of a basin and on the southeast flank of a large dome. Here the top of the dome is ¼ mile northwest of production.

The Browning pool in the west part of T. 22 S., R. 10 E., lies at the base of steep west dip, about 2 miles west of a general terracing and immediately east of a syncline and basin.

The Pixlee area in the northwest part of T. 22 S., R. 10 E., lies west and southwest of a general "high" dipping northwest across the north part of the township. Part of the Pixlee wells are producing from the "First break" in the "Mississippi lime."

The Atyeo pool of southwestern Lyon County is on the west flank of the "high" plunging northwest from T. 22 S., R. 10 E.

The Polhamus-Marshall pool in T. 24 S., R. 9 E., and T. 25 S., R. 9 E., is on the west flank of a dome, the long axis trending northeast and southwest.

Farther northeast along the trend, the Aagard pool in the east-central part of T. 24 S., R. 9 E., is on the west and northwest flank of a long dome trending northeast and southwest. Production is also obtained farther northeast through a syncline in Sec. 1, T. 24 S., R. 9 E.

In the southwest part of T. 23 S., R. 10 E., the Thrall pool is on the northwest flank of a large terrace having a small closure.

The Burkett pool in the east-central part of T. 23 S., R. 10 E., is on the southwest slope of a long narrow nose and, extending down and off the nose, crosses a basin on the northeast. This nose and basin trend northwest and southeast.

The Seeley pool in the southwestern part of T. 22 S., R. 11 E., and the northwestern part of T. 23 S., R. 11 E., lies east of a west dip that is steeper than ordinary, and approximately 1 mile west of a general flat area that extends 5 miles north and south. Here a cross trend extends northwest and southeast from the Seeley pool of the main trend.

In the west-central part of T. 22 S., R. 11 E., the Harris and Greenwood pools are located on normal northwest dip.

Production northwest from the Harris pool is termed the "DeMalorie-Souder pool." The south part is in a syncline, and the north part lies on the south flanks of two pronounced domes.

The Clark-Wick pool, in the south-central part of T. 22 S., R. 11 E., is on the northwest flank of a terrace.

The Madison pool (Fig. 3) is in the east-central part of T. 22 S., R. 11 E., on the west flank of a large terrace, east of a steep west dip. The long axis of the terrace extends east and west, and there is a pronounced syncline north and south of the terrace.

The Fankhouser pool is in the south part of T. 21 S., R. 12 E., and north part of T. 22 S., R. 12 E., on a northwest-plunging nose.

The Lamont pool trends northwest and southeast in the southeastern part of T. 22 S., R. 12 E., and the southwest part of T. 22 S., R. 13 E. It is located on a practically normal northwest dip, with a steep dip east and west of it, and a large basin on the north.

The Shambaugh pool extends from Sec. 27 to Sec. 4, T. 23 S., R. 13 E., and is a sand lens above the "Mississippi lime" in the center of the Virgil field which produces from the "First break" in that lime.

The Ellis pool in the southeastern part of T. 23 S., R. 11 E., is southeast of a deep basin and on the north flank of a nose dipping northwest.

In the southwest part of T. 24 S., R. 11 E., and the southeast part of T. 24 S., R. 10 E., the Wiggins pool is on a terrace. The north extensions along the west part of the township are in a regional syncline.

Between the Madison and Clark-Wick pools in T. 22 S., R. 11 E., production pinches out in the syncline, and at the north end of the Madison pool production stops at the syncline. Also between the Thrall and Burkett pools in T. 23 S., R. 10 E., production stops at the intervening syncline.

Subsurface structure on the top of the "Mississippi lime" corresponds very closely with the surface structure. Any differences may be due to erosion of the top of the "Mississippi lime," to poor well logs, or to lack of wells drilled to the Mississippian.

If there is any relation between structural geology and deposition of the Bartlesville sand bodies, it is not known at the present time what that relation may be. On one dome the producing sand body lies on the northwest, and on another dome it is on the south or southeast side. In one place production may be on steep dip, and in another it is on a terrace, or even normal dip. In some places production pinches out at the synclines, and in others it crosses synclines. Many producing trends extend at right angles to the long axis of structural "highs."

CONCLUSIONS

In some of the cross sections the dip on the top of the Bartlesville sand corresponds in a general way with the dip on the base of the Kansas City formation.

In most of the cross sections along the short axis of the sand bodies the sand is arched in the central part of the section, with each end lower than the arched part. In some of the cross sections the sand bodies are thick in the middle and thin out at the ends; in other sections the sand is thick at one end and in the middle and thins out at the other end. Thin-

ning of the sand bodies may be abrupt or gradual; there is no general rule in this respect.

The shape of the sand bodies and the pattern of the trends do not point to stream-channel deposits but to sand bars as being the type of the Bartlesville sand bodies in the main trends of the Greenwood County district. It is possible that some of the sand bodies in the cross trends may be due to stream-channel fillings. Our present information indicates that the possible origin of the Bartlesville sand deposits in the main trends of the Greenwood County district is to be found in sand bars and tidal delta bars created by the action of oceanic waves and currents or tides near a shore line.

Structure as represented by the surface beds, the base of the Kansas City formation, and the top of the "Mississippi lime" seems to conform, but there seems to be no definite relation between the Bartlesville sand deposits and structure except that few of them overlie "Mississippi lime" buried hills. Hence there appears to be no relation between structures on the surface beds, the Kansas City formation, the top of the "Mississippi lime," and the accumulation of oil in the Bartlesville sand trends of the Greenwood County district of Kansas. Since the Bartlesville sand bodies are lenticular, they themselves form structural "highs" or traps, which are excellent reservoirs for the accumulation of oil.

EL DORADO OIL FIELD, BUTLER COUNTY, KANSAS[1]

JOHN R. REEVES[2]
El Dorado, Kansas

ABSTRACT

The El Dorado oil field is the largest in Kansas and one of the largest in the United States. Until its discovery in 1916, little oil had been produced in Kansas. Since that time the state has been one of the leading producers of petroleum. The accumulation of oil and gas is due to the existence of a buried anticline over which the younger rocks have been folded a lesser amount. Oil and gas are found in these younger rocks, but the major production of oil has come from the Ordovician at the unconformity between this system and the Pennsylvanian.

The anticline, with a total structural relief of approximately 1,400 feet, is typical of the "Granite ridge" of which it is a part. Faulting and most of the folding is confined to the pre-Pennsylvanian rocks, although there is closure of 150 feet on the surface beds. Because of the erosion which took place after the major uplift, the lower part of the Ordovician "Siliceous lime" is in contact with the upper part of the Pennsylvanian Cherokee formation, the unconformity being measured by the absence of approximately 1,400 feet of sediments. The stratigraphy of the pre-Pennsylvanian is typical of that of south-central Kansas.

GENERAL STATEMENT

The El Dorado oil field is in central Butler County, Kansas, in T. 25 and 26 S., R. 4 and 5 E.

Oil and gas were discovered on this anticline in 1915. Development was rapid during and immediately after the war period, and a daily maximum production of 116,000 barrels was reached in 1918. The anticline covers 40 square miles, nearly all of which is productive.

The El Dorado anticline is a part of the "Granite ridge," or Nemaha Mountains, of Kansas. Its stratigraphy and structure (Figs. 1 and 2) are more or less typical of that "ridge," which is the most important structural feature of the state.

STRATIGRAPHY[3]

The surface rocks are the Florence flint, Fort Riley limestone, Doyle shale, and Winfield limestone, belonging to the Chase formation of Per-

[1] Manuscript received by the editor, December 15, 1928. Published by permission of the Empire Oil and Refining Company.

[2] Resident geologist, Empire Oil and Refining Company.

[3] The geology of this field is described by A. E. Fath, "Geology of the El Dorado Oil and Gas Field, Butler County, Kansas," *Geol. Survey of Kansas Bull. 7* (1921). The

mian age. The Lower Permian and all of the Pennsylvanian above the Cherokee, which are not exposed, will not be discussed here. Where productive, mention of these formations is made under the heading "Oil and Gas Horizons." They are also shown graphically in Figure 3.

The Cherokee in this area is normally 250 feet in thickness. From the base of the anticline it decreases in thickness toward the crest, where only a few feet are present. It is composed of gray and black shales, sandy shale, and fine-grained sandstones.

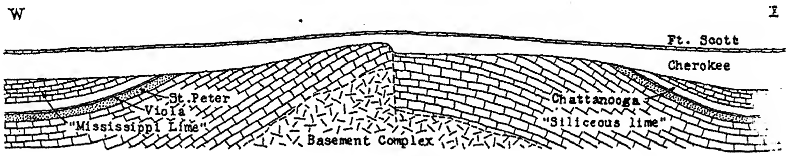


FIG. 1.—Ideal west-east cross section of El Dorado anticline from Sec. 7., T. 26 S., R. 4 E., to Sec. 12, T. 26 S., R. 5 E. Length, 12 miles; height, 1,200 feet.

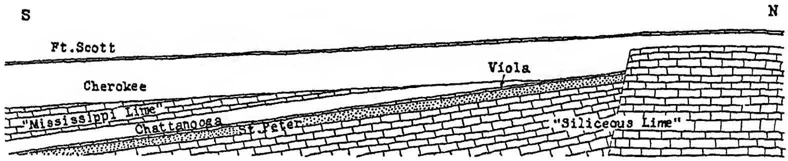
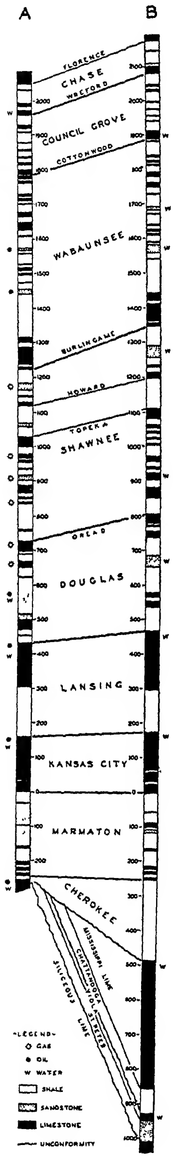


FIG. 2.—Ideal south-north cross section of southern part of El Dorado anticline from Sec. 31 to Sec. 8, T. 26 S., R. 5 E. Length, 5 miles; height, 500 feet.

The Mississippian is represented by the "Mississippi lime" and the Chattanooga shale. The thickness of the first normally ranges from 250 to 300 feet in this general area. It "wedges out" on the flanks of the anticline and is absent over the largest part of it, having been removed by erosion.

Stapleton oil zone is described as of Mississippian age in this bulletin, whereas it is of Ordovician age. Actually, the Stapleton is the producing part of the highest Ordovician formations on this truncated anticline. Other discussions of El Dorado are in the *Bulletin Amer. Assoc. Petrol. Geol.* as follows: Eliot Blackwelder, Vol. 4 (1920), p. 90; R. C. Moore, *ibid.*, p. 255; Aurin, Clark, and Trager, Vol. 5 (1921), p. 143; Rudolph Uhrlaub, *ibid.*, p. 421; D. W. Williams, *ibid.*, p. 507; A. W. McCoy, *ibid.*, p. 564; Ed. Bloesch, Vol. 6 (1922), p. 322; A. E. Fath, *ibid.*, p. 374. Also Dorsey Hager, (map of the surface geology) in W. H. Emmons' *Geology of Petroleum* (New York, 1921), p. 313.

The Chattanooga shale, which is questionably of Mississippian age, is composed of dark gray and black shale and is normally 70 feet thick. It is also absent over a large part of the anticline.



Ordovician formations underlie the Mississippian unconformably. The uppermost Ordovician formation is a cherty dolomitic limestone ranging from 15 feet in thickness on the south flank of the anticline to 50 feet in thickness on the north flank, a distance of approximately 12 miles. Generally it occupies the stratigraphic position of the Joachim of Missouri and the Viola of Oklahoma, but it has not been correlated on fossil evidence. For ease of reference it is here called the Viola, but no inference is made that it is that formation. This limestone is also present on the flanks of the anticline but absent on the crest.

Below the Viola is a sandstone formation 65 feet thick, consisting of white, rounded, frosted grains of quartz. Thin beds of green shale are irregularly present in it, and at the base occurs a persistent bed of green shale ranging from 10 to 20 feet in thickness. This formation is known locally as the "Wilcox" sand. It occupies the same position as the formation known by that name in northern Oklahoma and approximately that of the St. Peter sandstone of Missouri. It is normally present on the flanks of the anticline but has been eroded from the crest.

Below the St. Peter is the "Siliceous lime" composed of cherty dolomitic siliceous limestone. Normally the "Siliceous lime" is approximately 1,000 feet thick in this general area. During the period in which all the previously mentioned formations were removed from the crest of the anticline, the "Siliceous lime" was also deeply eroded. At one place in Sec. 11, T. 26 S.,

FIG. 3.—Type section for general area of El Dorado anticline, showing subsurface formations and oil and gas sands. All formations shown in normal thickness in feet. Log *A* is typical for crest of anticline. Log *B* is typical for area adjacent to anticline. Note thinning of section on anticline.

R. 4 E., it is only 350 feet thick, indicating that possibly 650 feet of it has been removed at this point.

Granite underlies the "Siliceous lime" and has been encountered in several wells on the El Dorado anticline at depths ranging from 2,700 to 3,600 feet, the former depth being on the crest. Although granite has been found in some of these wells, the use of the term "basement complex" would probably be more appropriate.

STRUCTURE

The axis of the main El Dorado anticline extends northeast and southwest. The closure of the surface beds amounts to approximately 150 feet. Superimposed on the main anticline are small domes with closures ranging from 20 to 40 feet. The east, or reverse, side of the structure is abrupt, with a dip on the surface beds of 150 feet per mile. The west side slopes more gently with a dip ranging from 50 to 75 feet per mile. For further details of the surface structure, refer to Figure 4 and to A. E. Fath.[1]

The subsurface structure of the lower Pennsylvanian beds conforms closely to that of the surface beds, with little if any increase in closure.

The structure of the pre-Pennsylvanian formations is much greater and more complex than that of the surface beds. By referring to Figure 5, it may be seen that the structure and relief of the Ordovician amounts to approximately 800 feet. On all but the highest parts of the anticline the contours on this map represent the structure of the Ordovician. On these high areas, however, they represent the surface of the Ordovician, for here the "Siliceous lime" is in unconformable contact with the Pennsylvanian and no control for contouring structure is available. The "Siliceous lime" is approximately 1,000 feet thick normally in this general area, but on the crest of the El Dorado anticline it is only 350 feet thick.[2] Thus, 650 feet of the formation was removed, necessitating uplift equal to that amount. On this basis, therefore, the total uplift of the anticline is near 1,400 feet. A large part of this movement is believed to be due to faulting rather than to folding.

In general, the structure of the Ordovician corresponds with that of the surface beds, but it is more intensified. Faults in the Ordovician are ordinarily represented on the surface by steep dips. The crests of the subsurface domes are directly under those of the surface domes, indicating that no shifting has taken place.

[1] "Geology of the El Dorado Oil and Gas Field, Butler County, Kansas," *Geol. Survey of Kansas Bull.* 7 (1921).

[2] Gypsy Oil Company's Shumway No. 27, NE. $\frac{1}{4}$, Sec. 11, T. 26 S., R. 4 E.

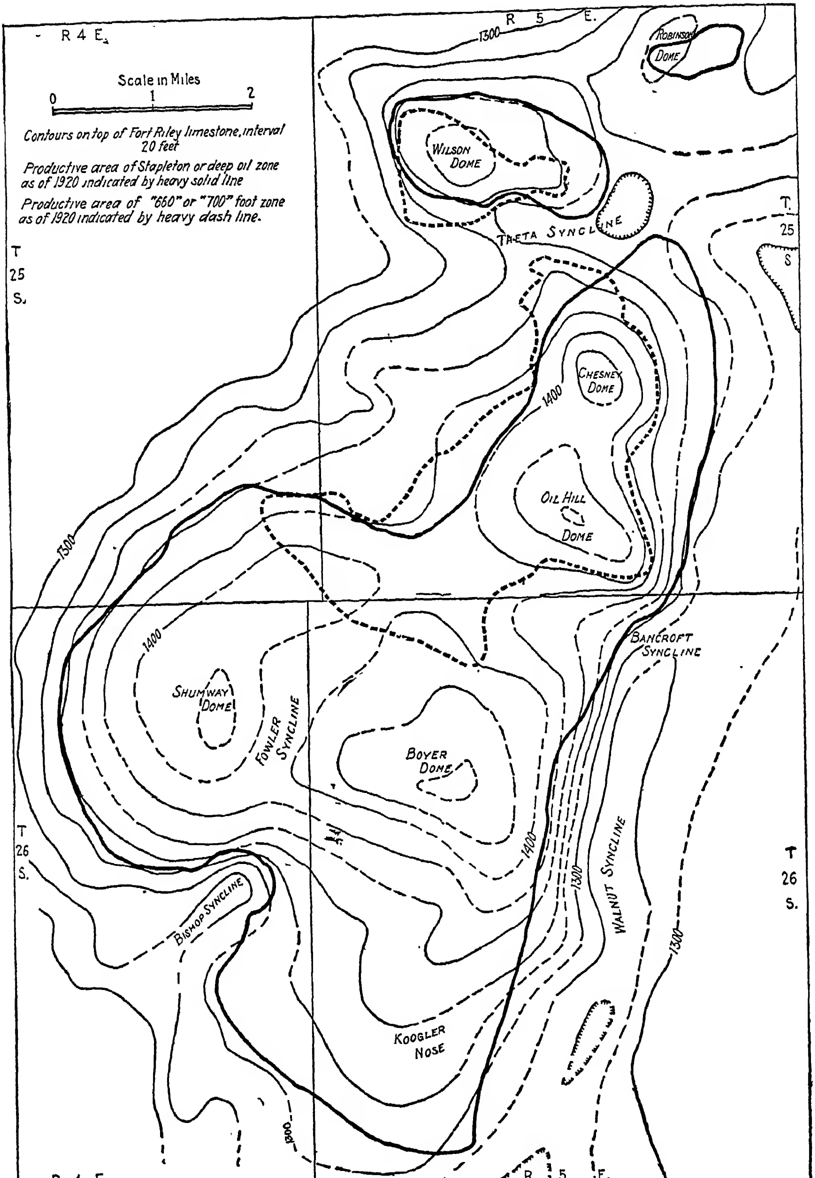


FIG. 4.—Outline structure map of El Dorado pool. (Adapted from A. E. Fath, *State Geol. Survey of Kansas Bull.* 7 [1921], Plate 14. Reproduced by permission from *Geology of Petroleum and Natural Gas* by E. R. Lilley, 1928 [D. Van Nostrand Co.]).

By referring to Figure 5, the strike and throw of the faults may be found. Of significance is the system formed by the faults and steep dips which reveal themselves in a fairly well-defined pattern. The fault trending northward on the east side of T. 26 S., R. 4 E., is definitely known to have a throw of 400 feet. That it continues northward into the area where

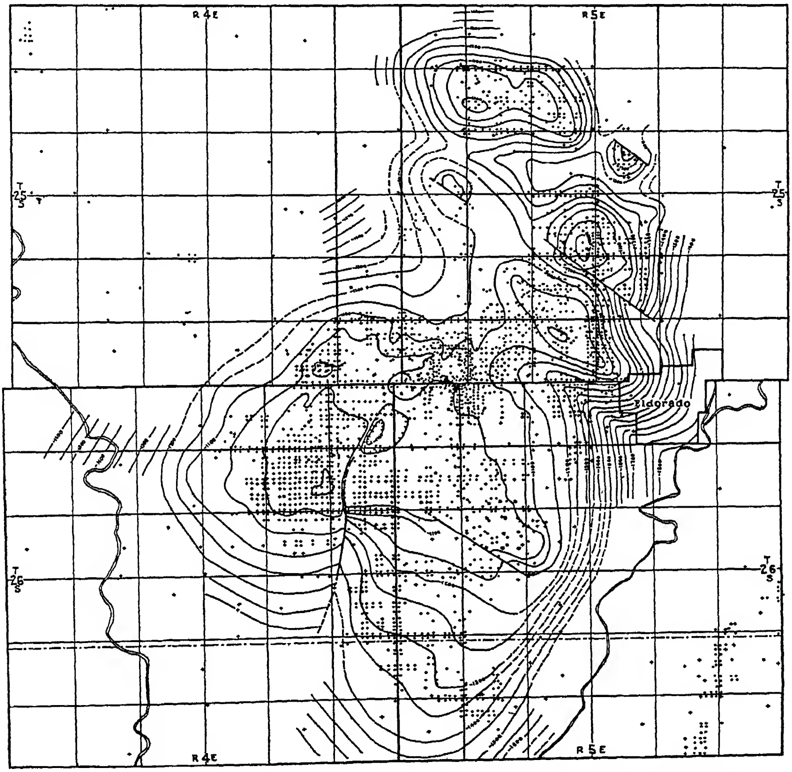


FIG. 5.—Structure of El Dorado anticline. Datum, top of Ordovician below sea-level. Contour interval, 50 feet. Width of area mapped, 12 miles.

the "Siliceous lime" is in contact with the Pennsylvanian is indicated by steep dip. In this area where structural control is lacking, the shallow depth to granite also suggests faulting. The fault with the northwest-southeast strike in T. 26 S., R. 5 E. is shown with an actual displacement of the surface of the unconformity of approximately 100 feet. However, the stratigraphic displacement is more than 175 feet, because the "Siliceous lime" on the upthrown side abuts the Viola and St. Peter on the downthrown side.

There is no actual evidence that the Pennsylvanian is faulted, although there is a suggestion of it in one place. Because of the possible inaccuracies of the well logs, this question will not be discussed.

OIL AND GAS HORIZONS

There are numerous producing horizons in the El Dorado field. In descending order the first oil sand occurs at a depth of approximately 600 feet in the upper part of the Admire shale of the Wabaunsee formation. The next oil sand occurs 115 feet lower, near the center of the Admire. The Admire, here composed almost entirely of shale, sandy shale, and sandstone, comprises the greater part of the Wabaunsee formation. These two sandstone horizons are not known to produce elsewhere in Kansas.

From approximately 900 feet to 1,500 feet in depth there are six horizons which produce gas. These are in the Wabaunsee, Shawnee, and the upper part of the Douglas formations. Some of the horizons are limestone, and others sandstone.

Oil occurs at a sandstone horizon in the lower part of the Douglas formation at a depth of about 1,550 feet; at the top of the Lansing limestone formation at about 1,700 feet; and at the top of the Kansas City limestone formation at about 2,000 feet. These are known as the 1,550-foot, 1,700-foot, and 2,000-foot sands.

On the east side of the field where the "Mississippi lime" wedges out, some oil occurs in this formation. A very few wells were completed in it in the early days but have since been abandoned.

The lowest producing zone, ranging in depth from 2,350 feet to 2,750 feet, is the Ordovician and has been called the "Stapleton zone," after the lease on which the discovery well of the field was drilled. It may be either the eroded surface of the Viola, St. Peter, or "Siliceous lime," or these formations down the dip from the truncated edges where they are entirely below the unconformity. There is practically no erosional débris at the unconformity. The oil occurs in the porous limestone of the Viola and "Siliceous lime" or the sandstone of the St. Peter. Generally, on part of the east and southeast sides of the anticline production extends down to the −1,500-contour but elsewhere only to the −1,100-contour.

The Ordovician and second Admire, or 700-foot sand, are the most important producing horizons in this field. All other oil horizons have had but comparatively few wells completed in them. The gas sands have been completely developed. The gravity of the oil from the Ordovician ranges from 33° to 36° Bé. Oil from other sands has a gravity of approximately 36° Bé.

The production of the El Dorado field has been as shown in Table I.

TABLE I

PRODUCTION, EL DORADO FIELD*

Year	Production per Year (in Barrels)	Average Daily Production (in Barrels)	Year	Production per Year (in Barrels)	Average Daily Production (in Barrels)
1916	Unknown	Unknown	1923	6,330,482	17,317
1917	19,915,569	54,563	1924	5,436,395	14,870
1918	29,198,145	79,720	1925	5,145,241	14,195
1919	17,613,272	48,250	1926	5,046,106	13,800
1920	14,379,061	39,390	1927	5,191,462	14,210
1921	14,828,554	40,620	1928 (first half)	2,417,852	13,280
1922	6,941,032	19,010			

* Data from *The Oil and Gas Journal*, Tulsa, Oklahoma. The field was discovered on October 15, 1915, and 9 wells were completed that year. At the end of 1916 there were 600 oil wells with an output estimated at 15,000 barrels a day.

CONCLUSIONS

The El Dorado anticline was first uplifted at the close of the Mississippian or early in the Pennsylvanian. This movement was partly folding and partly faulting. Folding amounting to 150 feet again took place some time after early Permian. Faulting in the pre-Pennsylvanian rocks certainly amounts to as much as 400 feet and probably more. After the first uplift the anticline was subjected to erosion, which removed possibly part of the lower Pennsylvanian, all of the Mississippian, and the Viola, St. Peter, and more than half of the "Siliceous lime" of the Ordovician. The anticline was an island during most of Cherokee time, depending on the exact time of the major uplift.

PINE ISLAND DEEP SANDS, CADDO PARISH, LOUISIANA[1]

A. F. CRIDER[2]
Shreveport, Louisiana

ABSTRACT

The development of the Pine Island deep sands followed the exhaustion of the oil from the so-called "Woodbine" sand.

The Glen Rose limestone is found in the Pine Island field immediately below the "Woodbine" sand at an approximate depth of 2,300 feet. The Washita-Fredericksburg sediments were deposited and eroded from the crest of the dome but occur around the flanks of the Pine Island uplift.

The Trinity group in this paper is separated into upper Glen Rose, 200 feet; anhydrite zone, 450 feet; lower Glen Rose limestone, 900 feet; and red shale and sand zone, 2,000 feet.

The main structural features of the region are the gentle folding of the Upper Cretaceous, which involves the entire area of the northern Sabine uplift and the more intense folding of the Comanche. The latter is confined to the Pine Island field. No faulting of any considerable magnitude is present.

Three oil zones and one gas horizon have been developed to date in the Comanche sediments of Pine Island.

The field has been outlined by dry holes, and the possibilities of deeper production are yet unknown.

LOCATION

The Pine Island oil field is in the eastern part of T. 21 N., R. 15 W., Caddo Parish, Louisiana. It is south of the Hosston shallow field and north and east of the old Caddo or Ferry Lake field.

HISTORY

The oil development of Pine Island began in 1917, when the Elton Oil Company drilled in its Hobbs No. 1 in Sec. 21, T. 21 N., R. 15 W., as a 150-barrel producer from the "Woodbine" sand at an approximate depth of 2,300 feet. The field was rapidly developed; and the "Woodbine" sand, on the edges of the field, soon began to make more or less salt water, which gradually encroached on the higher parts of the structure. At the present time the "Woodbine" production in this area is completely exhausted.

On the exhaustion of the "Woodbine" production, F. H. Wickett, who was then president of the Dixie Oil Company, Incorporated, began

[1] Presented before the Association at the Tulsa meeting, March 24, 1927. Manuscript received by the editor, August 31, 1928. Published by permission of the president of the Dixie Oil Company, Incorporated.

[2] 821 Ontario Street.

to deepen old "Woodbine" wells, believing that the oil had its origin in deeper formations. With the idea always in mind of drilling a 5,000-foot well in the Pine Island field, several wells were commenced for deep tests, but all found production before that depth was reached.

The first production below the "Woodbine" was found in the Glen Rose between 2,800 and 2,900 feet. This, however, was soon exhausted, and later the lower part of the Glen Rose became the objective on account of the large gas well encountered by the Dixie Oil Company in its Dillon No. 43 at a depth of 3,363 feet. The completion of that well on July 21, 1922, was the real beginning of the deep-sand development in Pine Island and northern Louisiana. There had been other deep wells drilled in the general territory, but Dillon No. 43 was the first commercial well completed in the lower part of the Glen Rose formation.

SURFACE STRATIGRAPHY

In the heart of the Pine Island field, highly cross-bedded sands and shales and a few boulders, all of Wilcox age, form the surface. On the north and west, Claiborne clays and sands of Cane River age overlie the Wilcox. Alluvium sediments blanket the stratified rocks at the east and south. Table I shows the type formations penetrated and the average thickness of each in the Pine Island field.

SUBSURFACE STRATIGRAPHY

EOCENE

An approximate thickness of 650 feet of Eocene Tertiary beds is present in the Pine Island field. These beds are sand, shale, and gumbo, with a small amount of lime in the Midway. In the drilling of wells, very little attention is paid to the nature of the formations until the Nacatoch is reached, at a minimum depth of 800 feet.

GULF SERIES

The Upper Cretaceous formations in this area have been given in detail in numerous publications, and space will not be taken here to describe them.

There are two well-marked horizons of the Upper Cretaceous used as key beds, both by drillers and geologists, in checking the formations of drilling wells. These are the Nacatoch sand and the Annona chalk. The Nacatoch formation is here a slightly calcareous sand and carries oil throughout the field, but is not sufficiently saturated to make producing wells. The top and the bottom of the chalk are both good key horizons

In the Dixie Oil Company's Dillon No. 65, Sec. 13, T. 21 N., R. 15 W., the top of the Comanche was encountered at a depth of 2,298 feet. The Comanche here is of Glen Rose age. In commenting on the samples from this horizon, A. L. Selig, who examined the cuttings under the microscope, says:

> The top of the Comanche was placed at 2,298 feet in this well, so the oil-bearing horizon occurs very close to the top. It is probable that the porosity is due to solution and secondary change to crystalline calcite close to the unconformable contact. The last sample at 2,315 to 2,317 feet, showed less calcite and a larger quantity of gray unaltered lime than the upper samples, which indicates that the drill penetrated the altered zone into solid limestone. This altered material is the so-called "Woodbine" or the 2,300-foot production of the Pine Island district.

In the center of the Pine Island field, Glen Rose, which is of Lower Cretaceous age, immediately underlies the "Woodbine" sand. The Washita and the Fredericksburg were probably deposited and later uplifted and subjected to erosion before the deposition of the Upper Cretaceous sediments, indicating that folding was active before the close of Comanche time and probably continued into the Upper Cretaceous. Red shale and sand, which are distinctive markers of Washita-Fredericksburg sediments of the surrounding area, are not found over the top of the Pine Island dome but are present on all sides of the structure.

Only a few determinable macroscopic fossils have been found in the Glen Rose sediments of Louisiana, and these fossils have a range through the greater part of the formation. Microscopic fossils have been of great assistance in working out the stratigraphic problems of the Pine Island field, but even these are of assistance in determining only two or three definite horizons. These fossiliferous horizons and the thick bed of anhydrite in the upper part of the Glen Rose make it comparatively easy to determine in advance where the producing gas and oil horizons will be encountered in drilling wells.

The interval between the base of the Annona chalk and the top of the anhydrite in the Cotton Valley field is 600 feet greater than between these two horizons in Pine Island. The interval between the top of the Nacatoch and the base of the chalk in the two fields is approximately the same.

The thick beds of Washita and Fredericksburg clay, sand, and limestone which are present in Cotton Valley have been eroded from Pine Island.

The Washita-Fredericksburg formations in northern Louisiana con-

tain more or less red sand, shale, and gumbo. These red materials should not be confused with the red sand, shale, and gumbo which occur in the lower part of the Comanche section. In some parts of northern Louisiana the two red formations are stratigraphically 1,800 feet or more apart. The red materials of Washita age, surrounding Pine Island, occur at a minimum depth of approximately 2,300 feet below the surface. This depth increases down the sides of the Sabine uplift. The depth of the lower Comanche red materials in Pine Island is about 4,000 feet, making an interval of 1,700 feet between the Washita red materials and the red materials of the lower part of the Comanche section.

The Ohio Oil Company's Smith No. 25, in Sec. 12, T. 21 N., R 15 W., entered the lower red shales at a depth of 3,990 feet, and went out of them at 4,896 feet, showing a thickness of 906 feet of red materials.

In the Humble Oil and Refining Company's Bliss and Weatherbee No. 1, Sec. 14, T. 19, R. 11 W., Bellevue field, the red, non-marine series of the lower Comanche is 2,515 feet in thickness. This may represent the full thickness of the lower red materials, as the bit penetrated marine limestone below the red series.

The bed of anhydrite in the upper part of the Glen Rose formation ranges from 400 to 500 feet in thickness. Glen Rose fossils which have been found above the anhydrite clearly establish the age of the anhydrite as Glen Rose.

In the Palmer Corporation's Davis No. 1, Cotton Valley field, Glen Rose fossils were found 718 feet above the top of the anhydrite.

In the Gulf Refining Company's Muslow No. 1, Sec. 35, T. 21 N., R. 15 W., Pine Island field, the top of the anhydrite was encountered at a depth of about 2,475 feet. The Glen Rose was passed through at a depth of 4,250 feet. With 718 feet of Glen Rose above the anhydrite in Cotton Valley and 1,775 feet below the top of the anhydrite in the Gulf's Muslow well, 2,493 feet of Glen Rose has been penetrated in northern Louisiana.

In the Ohio Oil Company's Smith No. 25, previously mentioned, the bottom of the hole was still in Lower Cretaceous, although 3,785 feet of formations of that age had been penetrated. This perhaps represents the maximum thickness of Lower Cretaceous sediments penetrated in northern Louisiana.

STRUCTURAL CONDITIONS

The Pine Island field is a very small dome part way down the northeast flank of the Sabine uplift.

It is not possible to map the surface structure of the Pine Island field proper. The surface sands and clays of Wilcox and Claiborne ages are

highly cross-bedded, making it impossible to distinguish between true dips and cross-bedding. Figure 1 is a structural contour map of the Nacatoch sand below sea-level. This map shows Pine Island (T. 21 N., R. 15 W.) as a part of the general uplift affecting all of Caddo.

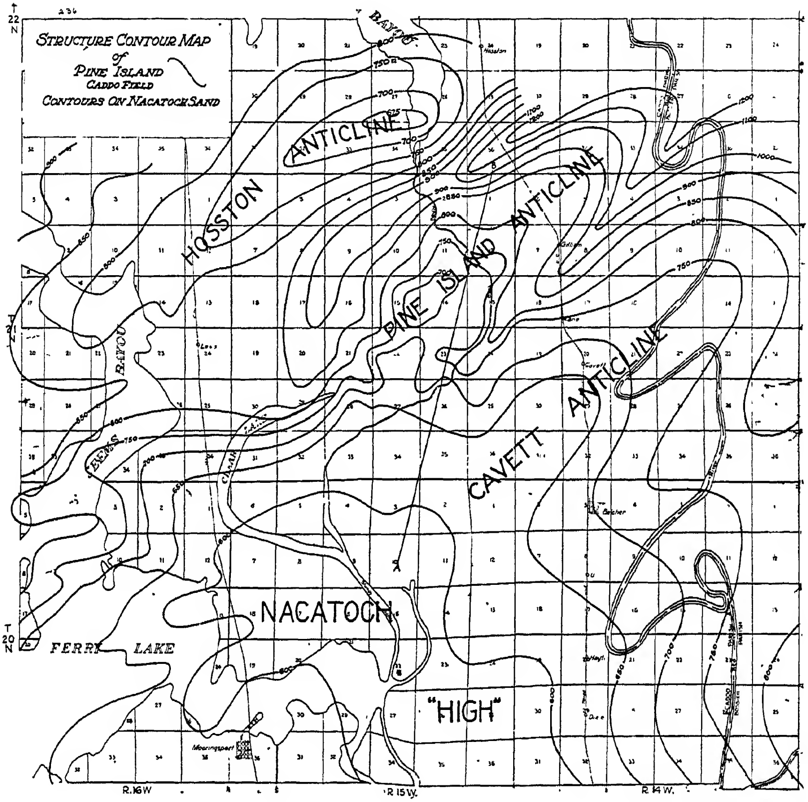


FIG. 1.—Structure contour map of the top of the Nacatoch sand, in feet below sea-level, by J. Y. Snyder and A. F. Crider. Width of area mapped, 16½ miles.

The highest part of the Nacatoch sand is in the area along Stumpy Bayou and the eastern end of Ferry Lake, where it is less than 600 feet below sea-level. From this general Nacatoch "high" radiate two prominent anticlinal noses. The northern is the Pine Island or Gilliam anticline, and the southern is here given the name of "Cavett" anticline. More or less paralleling these two anticlines is the Hosston anticline north and west of Pine Island, and separated from it by a deep syncline, 200 feet or more below the crests of the two structures.

The Nacatoch rises somewhat higher on the Hosston anticline than it does on the Pine Island anticline. Both the Hosston and the Pine Island structures show closure of 50 feet or more on the Nacatoch.

The Cavett anticline shows a slight closure on the Nacatoch if mapped by contours with an interval of less than 50 feet.

It is of interest to note that the Nacatoch sand is barren of oil and gas in the area of the Caddo and Pine Island fields. On the highest part of the Hosston field it produced gas, and down the north slope it was productive of oil. At the same structural horizon on the east and south sides, neither oil nor gas was present.

On the Cavett anticline oil and gas were produced from the Nacatoch sand.

A structure contour map with 50-foot intervals on the Nacatoch fails to reveal any evidence of faulting in the Pine Island field. There is evidence of fracturing in the Glen Rose limestones, through which oil and gas have migrated; but there still is lacking the proof that this fracturing is associated with pronounced faulting.

Figure 2 shows structural conditions on top of the first red shale, which is approximately the same as a contour map of the "Woodbine" producing horizon. It covers the same area as that on the Nacatoch sand. A comparison of the Nacatoch and the red-shale maps shows a marked change in the general deformation. In the red-shale map, Pine Island and Cavett anticlines have merged into one, about 100 feet lower than the Ferry Lake "high." Hosston, which was higher on the Nacatoch than Pine Island, is lower on the red shales. The Ferry Lake "high" has shifted 4 or 5 miles toward the west and is separated from the Jeems Bayou "high" on the northwest by a high saddle, and the Jeems Bayou "high" is separated from the Hosston "high" by a low saddle. The big production of the "Woodbine" sand followed closely the "highs" as shown on this map.

The influence of pre-Upper Cretaceous folding is shown on the map in hatch. The hatched area includes Pine Island field and the greater part of the Cavett anticline. The Washita red shales were probably deposited across what is now the Pine Island dome. It was later uplifted above the surrounding country by crustal movements similar to the forces that have produced salt domes, where only small areas are involved in the movement. This sharply folded area was subjected to more severe erosion than the surrounding area, and the Washita red shales were removed from the top of the dome. No evidence of salt has yet been discovered in Pine Island or in Bellevue, another dome where a very limited area is involved in the folding.

Figure 3 shows the structural conditions on top of the Dillon sand, the zone of large oölites.

Intensive drilling of Pine Island field has developed two separate domes, one in the E. $\frac{1}{2}$, Sec. 14, and the other in the NW. $\frac{1}{4}$, Sec. 23, and the SE. $\frac{1}{4}$, Sec. 14, T. 21 N., R. 15 W.

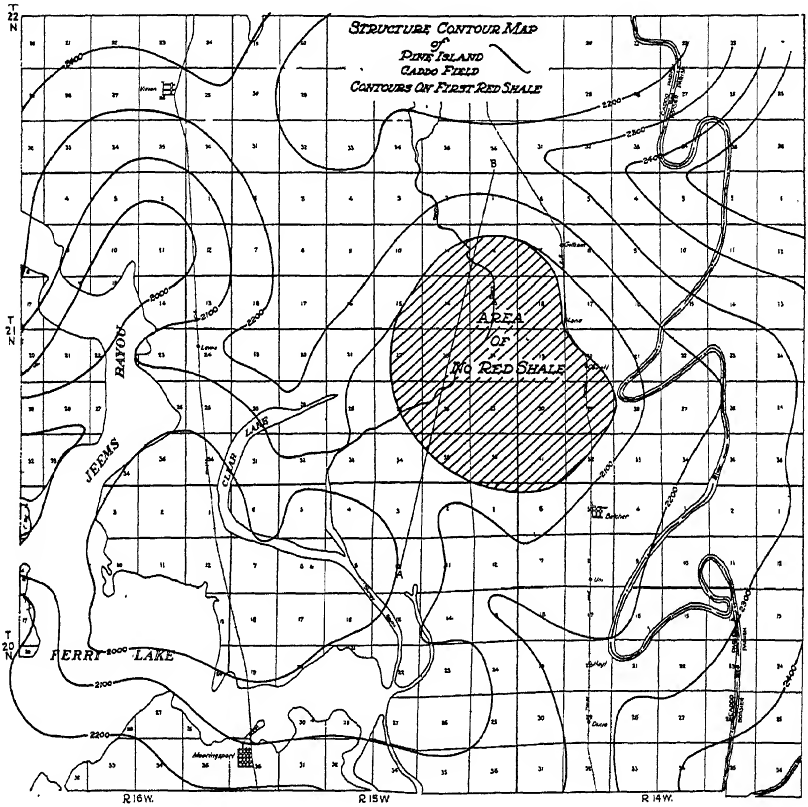


FIG. 2.—Structure contour map of the top of the first red shale, in feet below sea-level. Width of area mapped, $16\frac{1}{2}$ miles.

Figure 4 shows the Glen Rose uplift with Washita-Fredericksburg sediments, which fail to cover completely the Glen Rose uplift, with an unconformity between the Upper Cretaceous and the Lower Cretaceous.

The two "highs" are separated by a deep syncline which extends from the northwest. The contrast between the type of folding as shown in Figure 3 and the Nacatoch and red-shale contour maps, Figure 1, is very

striking and indicates a different origin of forces for the two types of folding. The force necessary to produce the results shown in Figure 3 must have been an upward vertical movement of great intensity at one focal point. This could have resulted from a deeply-buried intruded laccolith.

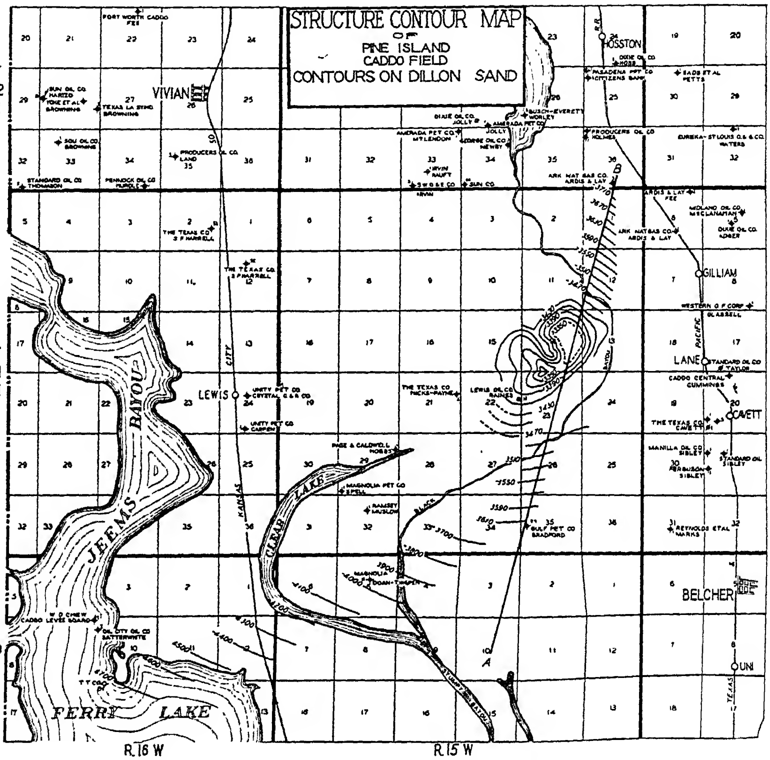


FIG. 3.—Only a few of the deep wells whose logs were used in contouring the Dillon sand are shown on this map.

The stresses which developed the sharply folded structure, as shown on the Dillon sand, were quite different from those which formed the Nacatoch and the red-shale folds. The latter are gentle and affect an area of 2,500 square miles or more, including practically all of the northern part of the Sabine uplift.

The "Woodbine"-Nacatoch folds resulted from lateral stresses, the force probably originating from both sides, causing the formations to buckle up in the center. This was the culmination of the tectonic movements which rounded out and completed the Sabine uplift.

The force which developed the Dillon sand structure was at least more intense than that forming the Nacatoch and "Woodbine" structures, and the major part of the Dillon folding occurred before the deposition of the Upper Cretaceous sediments.

During the interval between the intense folding of the Comanche sediments and the later, more gentle warping of the "Woodbine" and the Nacatoch formations, there was a long time interval when the present Pine Island field was high land subjected to erosion and was almost peneplaned, removing the Washita-Fredericksburg sediments from the crest of the dome. Later the entire area was submerged, and the Upper Cretaceous sediments completely covered the eroded edges of the Comanche rocks.

Later, during the post-Comanche uplift, which involved all of the formations up to and including the Claiborne, the Glen Rose fold of the Pine Island area was intensified and brought to its present state of structural development. No major tectonic movements of any consequence have affected the formations of the Pine Island area since the close of Claiborne time.

There is a dip on Comanche beds of more than 1,300 feet from the crest of the Pine Island field to The Texas Company's B-1, in Ferry Lake, or approximately 136 feet to the mile. It is of interest to

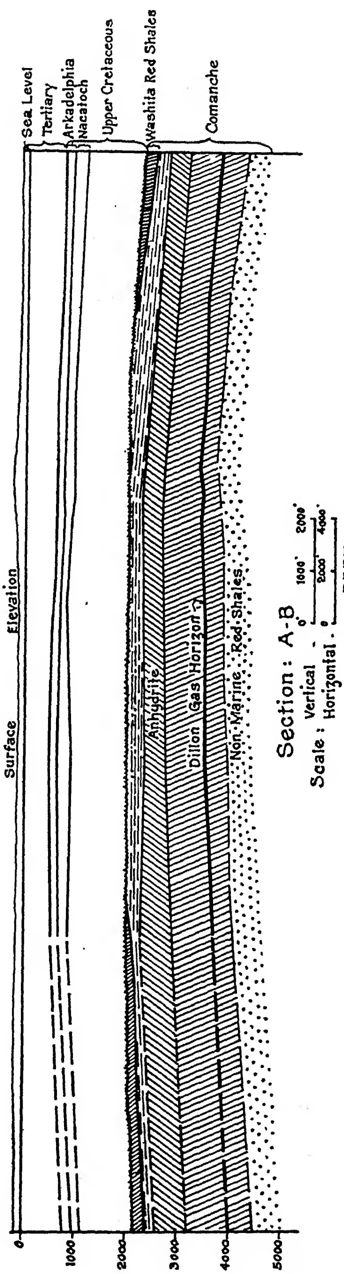


FIG. 4.—For location of section, see Figures 1, 2, and 3.

note the fact that the red-shale "high" coincides with the Dillon sand "high," except that the former is more extensive than the latter.

Figure 4 shows a cross section from north to south across the highest part of Pine Island.

OIL AND GAS RESERVOIRS

There are four distinct types of Comanche sediments in the Pine Island field in which oil and gas have accumulated. These are anhydrite, highly creviced marine limestones, oölitic limestones, and non-marine quartz sand.

ANHYDRITE OIL HORIZON

The first producing horizon in the Comanche sediments has recently been found in the lower half of the anhydrite bed at a depth of about 2,700 feet. Showings of oil and gas from this horizon have been reported from several deep tests on the highest parts of the Pine Island structure; but the first producing well to be completed in the anhydrite was the Dixie Company's Dillon No. 91, which was completed as a 90-barrel oil well. Up to the present time this is the only commercial well completed in this horizon.

TWENTY-NINE-HUNDRED-FOOT OIL HORIZON

So many of the newly discovered pay "sands" were first discovered on the Dillon lease that it is not possible to give each a separate farm name.

The 2,900-foot pay "sand" occurs just below the base of the anhydrite bed. It is a fractured oölitic limestone of very small *Miliolidae* (*Foraminifera*) with exterior coating. A few small producers were completed in this "sand" by the Dixie Oil Company in the early development of the Pine Island field, but the production rapidly declined and the wells were soon abandoned. None of these wells is producing at present.

It is of interest to note that the deep gas and oil of Cotton Valley come from approximately the same stratigraphic horizon as the 2,900-foot "pay" in Pine Island.

"DILLON" GAS HORIZON

In 1922 the Dixie Oil Company, in deepening Dillon No. 43 from the "Woodbine" sand, encountered a large volume of gas at a depth of 3,623 feet. This was the first producing gas well from the lower Glen Rose formation. The volume of the gas was estimated at 45,000,000 cubic feet a day, with a pressure greater than 1,550 pounds.

The name "Dillon" gas horizon is here proposed for the geologic name of this producing horizon. It is easily recognized by its composition of

large spherical oölites loosely cemented by calcium carbonate. Its position in the geologic column ranges from 1,100 to 1,200 feet below the top of the anhydrite. It is the first definite marker below the base of the anhydrite.

The gas from the Dillon gas horizon is rich in gasoline. The amount of gasoline varies from 300 to 400 gallons per million cubic feet of gas.

"DIXIE" OIL HORIZON

It is somewhat unusual at present to name a producing horizon for an individual or a company, but to the Dixie Oil Company is largely due the credit of developing the deep oil and gas horizons of the Pine Island field, and the name "Dixie" oil horizon is here proposed for the oil-producing horizon which occurs approximately 90 feet below the Dillon gas horizon. It is generally a very compact limestone composed of elongate fragments of fossils with thin black exterior coating, highly fractured and creviced, in the crevices of which the oil, accompanied by gas and water, has accumulated. The first oil well completed in the Dixie horizon also was located on the Dillon lease. Its geologic position is approximately 90 feet below the Dillon gas horizon and 193 feet above the "Herndon" oil sand, which is described hereafter.

The rich gasoline found in the Dixie's Dillon No. 43 at a depth of 3,623 feet gave encouragement for still deeper drilling, and when Dillon No. 53 was deepened from the "Woodbine" sand, the heavy gas encountered in Dillon No. 43 was cased off, and about 90 feet below the gas horizon the well came in, producing 400 barrels of oil, 25,000,000 cubic feet of gas, and 3,000 barrels of salt water a day.

The highly-creviced nature of the limestone in which the Dixie oil has accumulated may be known by the movement of liquids between wells and the effect the completion of one well may have on other wells in the field.

In the drilling of Dixie Oil Company's Dillon No. 53, the first well to produce from the Dixie horizon, a large amount of iron oxide was used to hold down the heavy gas pressure from the Dillon gas horizon until casing was set through the gas horizon.

When the Dixie's Noel A-1, which is located 1,000 feet or more east of Dillon No. 53, was completed as a 25-barrel oil well, with 3,000,000 cubic feet of gas and 3,000 barrels of salt water, the iron oxide which was placed in Dillon No. 53 began to appear and colored the water very materially. Samples of the water were taken and analyzed to make sure the coloring matter was iron oxide. As no other iron oxide had been used

gas well in the deep sand, produced gas for five years, with practically no water.

Oil wells producing from the Dixie creviced limestone horizon higher on the structure than the Dixie's Dillon No. 43 have invariably contained a large amount of salt water. The most prolific oil production has come from the highest points structurally.

"HERNDON" OIL SAND

The oldest producing horizon, stratigraphically, in the Pine Island field comes from a fine-grained quartz sand, within, but near the top of, the red non-marine sediments at depths ranging from 3,900 to 4,000 feet, depending on the elevation of the surface and the position on the structure.

The Texas Company's Herndon No. A-6 was the first large producing well completed in this sand, and the name "Herndon" oil sand is proposed for this producing horizon. This well was located in Sec. 13, T. 21 N., R. 15 W., about 30 feet down from the crest of the structure, and was completed as a 500-barrel well.

The Herndon oil sand is a reddish sharp quartz sand which occurs 280 feet or more below the Dillon oölitic gas horizon. In some wells, 10 feet or more of non-calcareous red shales overlie the oil sand; and in other wells, the interval between the red shales and the Herndon oil sand is much greater. In some wells completed to date there are three or four saturated oil sands in the first 50 feet below the top of the red shales. It is possible that still larger wells may be completed in this sand series, where the sand is more porous.

PRODUCTION

Production figures of the deep sands have not been separated from those of the other horizons, so that it is not possible to determine the amount of oil that has been produced from the deep sands of the Pine Island field.

The erratic nature of the pay horizons, the expense of drilling the wells, and the limited producing area have made the field as a whole of doubtful economic value. Individual wells of different companies operating in the field have shown results on the right side of the ledger, but these good wells have had to "carry" many poor wells which will never pay out; and this burden, in addition to the dry holes that have been drilled in the producing area and around the edges of the field, has made the field as a whole unprofitable.

Production curves on two individual wells are given in Figure 5. These are from two different horizons. No. 1 is from the Dixie Oil Company's Dillon No. 53. The production is from the Dixie limestone horizon at a depth of 3,757 feet. The well flowed from November, 1926, to June 16, 1927. It was pumped only four months after it stopped flowing, when the economic limit of production was so small that it was abandoned on November 1, 1927.

Well No. 2 of Figure 5 was the Dixie's Dillon No. 29. The production from this well came from 2,887 feet, the horizon just below the anhydrite. This was also a limestone horizon, and the production from this "pay" was not profitable.

FUTURE OF THE FIELD

The producing area of the Pine Island field has been fully outlined by dry holes, and the sands thoroughly tested. The present producing area is limited to less than 500 acres.

The possibilities of increasing the production in the producing sands developed to date are not encouraging. The future of the field, therefore, lies in the possibilities of the discovery of some deeper pay zone.

The lowest "pay" thus far developed is approximately 4,000 feet deep. Below this lie 2,000 feet of red non-marine shales and sands, which are barren of oil and gas. Below the non-marine red sediments are more marine formations, which, under favorable structural conditions, may be productive of oil and gas. A deep test near the top of the structure is now being drilled by the Dixie Oil Company, which will test the sands immediately below the non-marine red formations. Should this prove to be a producing well from the lower marine formations, it will give encouragement for additional tests. A dry hole at this depth will doubtless tend to discourage deeper drilling.[1]

[1] Since this paper was written the Dixie Oil Company, Incorporated, has thrown new light on the deeper formations in the Pine Island field in the drilling of Dillon No. 92. In this well Comanche strata were encountered at a depth of 2,260 feet. From 2,260 to 3,895 feet were marine limestones, shales, and sands. From 3,895 feet non-marine red shales and sands continued to a depth of 5,925 feet. At that depth, marine shales and limestones continued to the total depth of the hole, 6,351 feet. The well penetrated 4,091 feet of Comanche. Red non-marine shales and sands from 3,895 feet to 5,925 feet were barren of fossils. The exact age of the marine shales and limestones below 5,925 feet has not been determined, but it is definitely Comanche. A string of $4\frac{3}{4}$-inch casing was set at 6,104 feet and when the well was tested it showed 192,000 cubic feet of gas and a showing of high-gravity oil.—A. F. C.

STRUCTURE OF CADDO FIELD, CADDO PARISH, LOUISIANA[1]

CORBIN D. FLETCHER[2]
Shreveport, Louisiana

ABSTRACT

Caddo is the oldest oil field in Louisiana and was discovered and almost wholly developed before geology became an essential part of the oil business. The writer believes that, although the so-called "Woodbine" sand, the main oil-bearing horizon, may be in part the equivalent of the Woodbine formation of Texas, it also includes several sands both above and below a pronounced unconformity between Upper and Lower Cretaceous rocks and is in part Tokio and in part Washita in age.

INTRODUCTION

The Caddo oil and gas field in the northwestern corner of Louisiana was discovered in 1904, sixty-three years after the discovery of oil at Nacogdoches, Texas, ten years after the discovery at Corsicana, and three years after the Lucas gusher at Spindletop. The discovery well was drilled because of gas seepages, in pools of water and in Caddo Lake, of sufficient size to furnish a domestic supply. Harris[3] and Matson[4] have described the field, and the present paper is designed merely to portray the present conception of the structural geology of the field and not to discuss the development of many years ago or drilling in recent years which followed the discovery of the Pine Island field described by Crider (p. 168).

Caddo is the oldest field in Louisiana. New wells, most of which have been drilled for production deeper than the famous "Woodbine" sand, have shown that the structure is not merely a broad dome with many subsidiary folds and a complete and conformable stratigraphic succession of rocks from the Lower Cretaceous to the Claiborne group of the Eocene. Both the surface and underground geology are complicated by several unconformities, the most important of which is between the Upper and the Lower Cretaceous.

[1] Manuscript received by the editor, November 15, 1928.

[2] Gulf Refining Company of Louisiana.

[3] G. D. Harris, "Oil and Gas in Louisiana," *U. S. Geol. Survey Bull. 429* (1910).

[4] G. C. Matson, "The Caddo Oil and Gas Field, Louisiana and Texas," *U. S. Geol. Survey Bull. 619* (1916).

The topography of the Caddo area shows slight relief, elevations ranging from 175 feet to 250 feet above sea-level. The surface is rolling, and the streams (locally termed "bayous") are meandering. Caddo (Ferry) Lake is at present artificially dammed at the eastern end but was, according to Harris and Veatch,[1] originally formed by the damming of the waters by a raft. The lake is very shallow and approximately 300 wells have been drilled in it. A large part of the surface bordering the lake and the bayous is swampy.

The productive area of the Caddo field, including the Hosston and Pine Island areas, covers approximately 125 square miles.

The writer wishes to acknowledge his indebtedness to the members of the Gulf Refining Company's geological department in the Shreveport office, and to W. C. Spooner, and Sidney Powers for their very helpful suggestions and criticisms in preparing this paper.

STRUCTURE

Harris recognized that the Caddo field is located near the north end of a very large, low domal area called the Sabine uplift, the axis of which is northwest-southeast. This feature is shown in the areal geology and in the underground correlations of formations. Somewhat similar uplifts have been recognized by means of areal geology in Florida and in Georgia.[2]

Drilling has revealed that in the Cretaceous rocks the Sabine uplift is but a part of a large structural feature embracing the oil fields of southern Arkansas and northern Louisiana, with the Monroe uplift on the east corresponding with and paralleling the Sabine uplift on the west.[3] The stratigraphy of this buried structure is complicated further by the overlap of the Upper Cretaceous and Eocene upon the Lower Cretaceous.[4]

The uplift is further disturbed by numerous minor faults aligned either northwest-southwest or northeast-southwest. In the Caddo field

[1] G. D. Harris and A. C. Veatch, "Preliminary Report on the Geology of Louisiana," *Louisiana Geol. Survey Rept. for* 1899, Part 5 (1900).

[2] L. W. Stephenson, *Geological Map of the Coastal Plain*, exhibited before the American Association of Petroleum Geologists at the Dallas meeting, March, 1926, also at Fort Worth, 1929.—EDITOR.

[3] W. C. Spooner, manuscript map for "A Report on the Oil Possibilities of Southern Arkansas," in preparation for the Arkansas Geological Survey.

[4] L. W. Stephenson, "Major Marine Transgressions and Regressions and Structural Features of the Gulf Coastal Plain," *Amer. Jour Sci.* (5), Vol. 16 (1928), pp. 281–98.

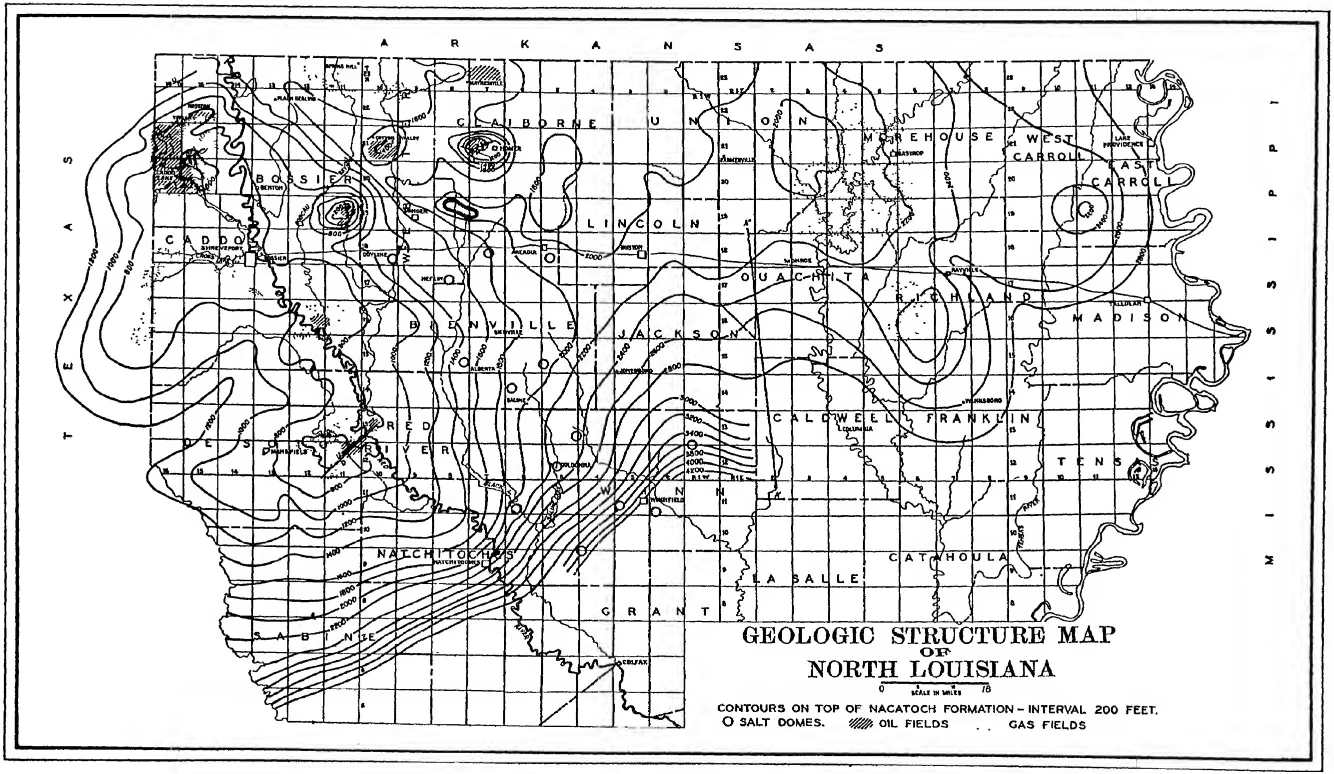


FIG. 1.—Geologic structure map of northern Louisiana, contoured on top of Nacatoch formation below sea-level. After W. C. Spooner.

these faults have an important bearing on the amount of production, both in the Upper Cretaceous and Comanche horizons. The axis of the Sabine uplift is northwest-southeast, and minor folding in both Upper and Lower Cretaceous is at right angles to its axis. The older formations are more sharply folded than the Upper Cretaceous, with a relief of as much as 2,000 feet on the crest of the uplift. The younger formations show only a fraction of that amount, with 200 feet as a maximum.

The average east and west dip from the crest of the main uplift is slightly less than 1° on the Upper Cretaceous and about $1\frac{1}{2}$° on the Lower Cretaceous.

STRATIGRAPHY

In Table I the stratigraphy of the Caddo area is given as known in 1916 and in 1926.[1]

GEOLOGIC HISTORY

It is now known that the Lower Cretaceous sea invaded southern Arkansas, covering all of Louisiana as well, and that the shore line lay near the western edge of Mississippi as represented by Stephenson. Sedimentary deposits of this age increased in thickness rapidly toward the southwest, and no evidence of the existence of the Sabine uplift prior to Lower Cretaceous time is indicated in the lithology or structure of these rocks. The presence of a 450-foot anhydrite zone in the Glen Rose makes possible the hypothesis that the salt in the interior salt domes comes from salt beds of that age, although salt has never been found in any wells penetrating the anhydrite, even in those drilled a long distance from any salt domes. Although this hypothesis is intriguing in many respects, the opinion is still held by many that the salt of northern Louisiana and eastern Texas has its origin in much older rocks than have yet been penetrated by the drill in these areas.

A discussion of the lithology and conformity of the divisions of Lower Cretaceous are not within the bounds of this paper. At present there is no direct evidence that the Sabine uplift was a positive element of Llanoris which furnished the material for the Ouachita geosyncline during the Carboniferous period as postulated by several geologists.[2] Nepheline

[1] Several changes in nomenclature were made by C. H. Dane *et al.*, "Oil-bearing Formations of Southwestern Arkansas," *U. S. Geol. Survey Press Notice 8823* (1926).

[2] Sidney Powers, "The Sabine Uplift," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 4 (1920), pp. 117–36; H. D. Miser, "Llanoria," *Amer. Jour. Sci.* (5), Vol. 2 (1921), pp. 61–89; A. W. McCoy, "A Short Sketch of the Paleogeography and Historical Geology of the Mid-Continent Oil District and Its Importance to Petroleum Geology," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 5 (1921), pp. 541–84.

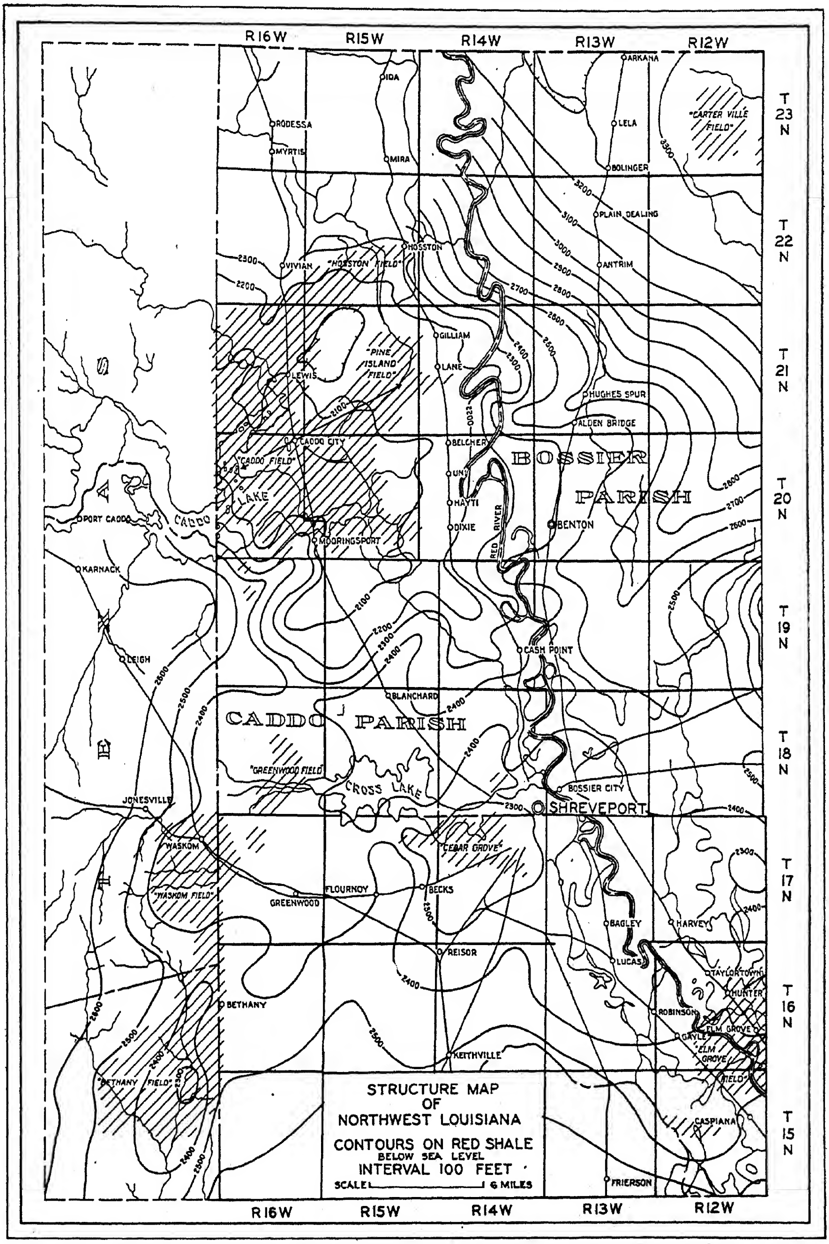


FIG. 2.—Structure map of northwestern Louisiana, contoured on first red shale encountered, whether "Woodbine" red in unconformity between Upper and Lower Cretaceous or red shale in Washita (Lower Cretaceous). Oil fields hatched.

TABLE I

Generalized Section of Formations in the Caddo Field

System	Series	1916* Formation	1926† Formation (Thickness in Feet)	1926† Member (Thickness in Feet)
Quaternary	Recent			
	Pleistocene			
Tertiary	Eocene	Claiborne group (St. Maurice)	Claiborne group (St. Maurice)‡	Minden sandy marl Sparta sand Cane River glauconitic marl
		Wilcox	Wilcox 300+	
		Midway	Midway shale 600–700	Includes part of Matson's Arkadelphia
Unconformity				
			Unconformity	
Cretaceous	Gulf	Arkadelphia clay	Arkadelphia clay 80–100	
		Nacatoch sand	Nacatoch sand 200–300	Lower part includes upper marl member of Matson's Marlbrook
		Marlbrook marl	Saratoga chalk	"Chalk rock" undifferentiated in Caddo field 475–500
			Marlbrook marl	
		Annona chalk	Annona chalk	
		Brownstown marl	Ozan 200–225	Ozan shales Buckrange sand "Blossom"
		Eagle Ford clay (including Blossom sand member at top¶)	Brownstown marl	Undifferentiated 450
			Tokio shale and sand	
		Woodbine sand	"Woodbine" sand (age questionable)	
	Unconformity			
	Comanche	Washita group	Washita group	Undifferentiated
		Fredericksburg group	Fredericksburg group	1,600 +
		Trinity group	Trinity group	Glen Rose, 1,650 Middle red, 2,000 Lower marine, 175+ Basement sands ?

* G. C. Matson, *op. cit.* † C. H. Dane *et al.*, *op. cit.*

‡ The Yegua, or upper Claiborne group, not represented in this area, and only the Cane River member of the St. Maurice represented on the flanks of the Sabine uplift.

¶ The "Blossom sand" is now regarded as basal Ozan and is termed the "Buckrange sand lentil" by Dane.

syenite and peridotite have been penetrated in wells in Grant, Cleveland, Ashley, and Chicot counties in southeastern Arkansas at depths ranging from 3,100 to 3,350 feet. The upper surface of these rocks, as shown in cores, is weathered, but the time of their intrusion is unknown.

After Lower Cretaceous time northern Louisiana and southern Arkansas were uplifted, and the major structural feature previously referred to was formed with its subsidiary Sabine and Monroe uplifts. The uplift was followed by a period of erosion during which the region was reduced to a plain of low relief. The Upper Cretaceous sediments were deposited in a sea that transgressed progressively, overlapping the older beds from west to east.

The Upper Cretaceous sea covered all of Louisiana with the possible exception of a restricted area in the northeastern corner of the state where Eocene rocks now rest on Lower Cretaceous rocks.

Upper Cretaceous strata are lithologically similar to those in Texas, but there is an upward lithologic transgression eastward, as pointed out by Hill many years ago, so that the "chalk" in Texas is far older than that in Alabama.

At the close of Cretaceous time there was another uplift, but of minor importance because the Midway formation has been recognized on all of the anticlinal folds. After Midway time there was a more pronounced uplift of the Sabine area and a clear definition of this feature because successively younger units of the Wilcox formation overlap the Midway. Also, the Wilcox thickens in all directions away from this uplift.

Again, at the close of Wilcox time there was upwarping, accompanied this time by extensive erosion, as indicated by outliers of rocks of Claiborne age which are found resting on the uplift unconformably on the Wilcox strata.

Subsequent movements consisted principally of rhythmic downwarping of the Gulf Coastal plain, as proved by rapid thickening of the formations gulfward and by successive fracture zones tangential to the Tertiary shore line, rotated and slightly uptilted on the gulfward side.[1] These accentuated the structural relief of the Sabine uplift.

LOCAL STRATIGRAPHY AND STRUCTURE

The Caddo field is divided into several smaller districts in local nomenclature, but from a structural point of view only three districts, or

[1] Some of them are shown by F. H. Lahee, "Oil and Gas Fields of the Mexia and Tehuacana Fault Zones, Texas," *Structure of Typical American Oil Fields*, Vol. I, p. 306.

fields, are recognized; these are Caddo (restricted), Pine Island, and Hosston.

Caddo, in the restricted sense, is composed of numerous small pools varying in size from less than 40 acres to 2 or 3 sections. Although it has been twenty-four years since Caddo produced its first oil, and although the greatest amount of development was completed many years ago, it has been only a short time since a new pool was discovered every few months. The last small boom occasioned by the opening of a new pool was in the early part of 1927.[1]

A structure map based on the top of the Nacatoch "Gas rock," such as that published by Matson,[2] shows no relation between local structure in this formation and the accumulation of oil in the "Woodbine." When a contour interval of less than 50 feet is used, local minor irregularities are such that the value of the map is destroyed, although the picture is strongly suggestive of a non-conformity between the Nacatoch and the overlying Arkadelphia. The presence of the manganese mineral, wad, at the contact between these two formations in several wells in the Caddo field further substantiates the idea of a short period of non-deposition, with a low, boggy island rising above the surface of the early Arkadelphia sea. It is not believed that such a non-conformity, if one exists, is present throughout a larger area than the Caddo field, if it indeed covers all of this field.

Production in the Caddo field proper is obtained from four, and probably six, different formations in the Upper Cretaceous and in the Washita group of the Comanche.

TABLE II

Oil and Gas Formations, Caddo Field

Upper Cretaceous	
Nacatoch "Gas rock"	gas, and oil in Hosston area
Saratoga, Marlbrook, and Annona "Chalk rock"	oil
Ozan "Sand rock"	little oil
"Woodbine" (probably three horizons in Upper Cretaceous and Comanche)	main oil horizon

The Nacatoch "Gas rock" has not been producing gas during the last five years, although every new well drilled in the area reports a small amount. In the Caddo field no oil has been found in this formation; but a

[1] Another boom occurred in 1929.—Editor.

[2] *Op. cit.*

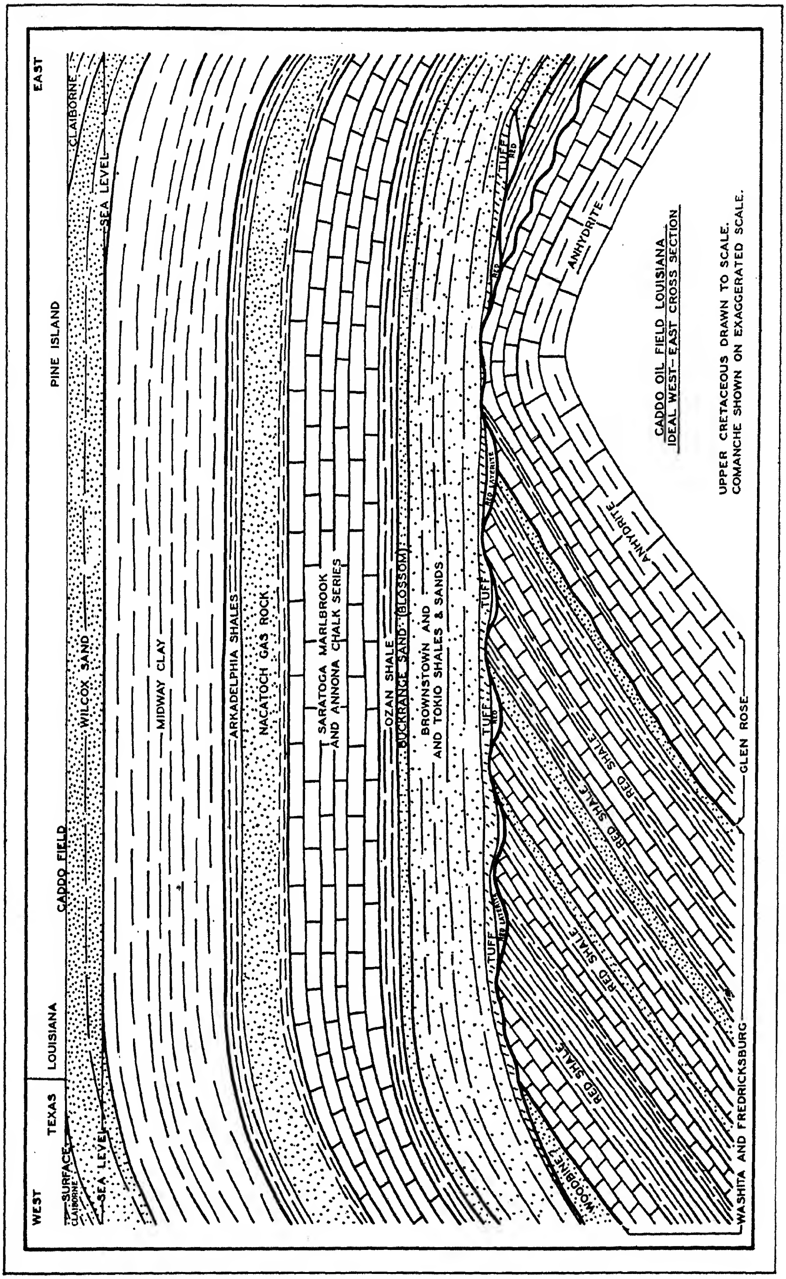


Fig. 3.—Ideal west-east cross section through Caddo field.

small amount of heavy oil, varying from 19° to 19.5° Bé. gravity, is produced from the Nacatoch in Pine Island, and the main production in the Hosston district is from that formation. The "Gas rock" is a hard, well-cemented sand and in some places is almost hard sandy limestone.

The "Chalk rock" produces oil, varying from 30° to 36° Bé. gravity, from a fractured zone in the chalk which is ordinarily about 100 feet below the top of the formation. Production in the "Chalk rock" is confined to a narrow strip, about ½ mile in width, following a northeast-southwest fault. The fault, which has a maximum throw of 80 feet, extends from Sec. 9, T. 20 N., R. 16 W., in a northeasterly direction to Pine Island and is seemingly lost in a maze of minor fracturing in Sec. 22, T. 21 N., R. 16 W., on the edge of the Pine Island structure. "Chalk rock" production in Pine Island has been prolific. Initial production of these wells has been as high as 1,800 barrels per day.

The Buckrange sand, of the Ozan formation, produces oil varying from 23° to 24° Bé. gravity, but the production is small and restricted to a small area on Jeems Bayou, which drains into Caddo (Ferry) Lake from the north and is located in the southwestern part of T. 21 N., R. 16 W., and the northwestern part of T. 20 N., R. 16 W. The oil has been found only in the extreme top of the sand, and salt water is encountered 2 or 3 feet below the top. No oil has been produced from the Ozan at any other place in the field. Initial productions are as much as 75 barrels.

Production in the Nacatoch is governed by small local faults and folds; in the Annona, by fracturing along a fault line; and in the Ozan, by a small local fold. In the so-called "Woodbine," however, production seems to be governed almost entirely by the amount of sand present. The "sand" is in reality several sands belonging in the Tokio, questionable Woodbine, and the Washita. One sand, or more, may be present. Initial production ranged from small wells of 15 or 20 barrels to those producing 9,000 barrels. Not a few flowing wells producing as much as 8,000 barrels of oil and several million feet of gas per day were offsets of dry holes. The field is dotted with these pools, some of which are separated by only a few hundred feet, others by intervals of half a mile.

The age of the "Woodbine" sand of Caddo has long been a subject of discussion, and it is to be regretted that an exhaustive petrographic study of well samples of this material has not been made. Stephenson[1] has correlated the Woodbine of Arkansas with the Woodbine of Texas on the

[1] L. W. Stephenson, "Notes on the Stratigraphy of the Upper Cretaceous Formations of Texas and Arkansas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 1 (January, 1927), pp. 1–17.

basis of lithology and stratigraphic position; and this writer, together with Dane,[1] has described the Arkansas section in great detail. However, there is nothing in the so-called "Woodbine" of Caddo which can be definitely correlated with the Woodbine of Arkansas. No two wells encounter exactly the same stratigraphic section in the producing horizon, and there are no fossils in part of the sand beds by which their age can be definitely determined. The material immediately above the first sand is black, micaceous, sandy shale which is definitely Tokio in age. The "sand" itself may be fine-textured, micaceous, well-cemented, quartz sand; medium coarse-textured quartz sand; or arenaceous tuff of mottled red, pink, purple, and white colors. In some localities these sands are overlain by brown, tufaceous shale, and in others the brown shale is underneath. In some places production is secured below a red shale bed. As most of the wells in the Caddo district were drilled before the practice of coring into the producing horizon became general, it has not been the writer's privilege to examine a great many cores from the so-called "Woodbine" sand. The following conclusions, however, have been drawn concerning the age of the producing sands and are here presented for consideration.

1. The varicolored arenaceous tuff commonly present immediately below shales of unquestionable Tokio age, and from which production is obtained in many places, is Tokio in age. It represents the base of the Tokio formation laid down upon a non-conformable surface, in most places probably laterite; and production is secured from the tuff where it was deposited in shallow basins in the surface of the previous land mass.

2. Part of the brown shales, red shales, and associated sands were laterite on the surface of the Comanche land mass and are not continuous, and production is dependent on their present lenticular character. The Trinity, which immediately underlies the Upper Cretaceous in Pine Island, and the Washita, immediately below the Upper Cretaceous in the remainder of the area, both furnish illustrations of production secured from porous, leached limestones originally exposed on the surface of the Comanche land area. Whether this leaching occurred prior or subsequent to the deposition of the Upper Cretaceous is not known.

3. Part of the brown and red shales, below which production is obtained, are Washita in age; and oil from the interbedded sands has been trapped through the sealing of the uptilted and beveled edges of the sands by impervious beds above. This has been proved in a few places and is undoubtedly the condition in other places.

In the amount of "Woodbine" production the thickness and porosity

[1] C. H. Dane, *op. cit.*

of the different sands have been a controlling factor. In some places, however, it is known that faulting has had much influence. In the western part of T. 20 N., R. 16 W. is a small fault with a northwest-southeast strike and a maximum throw of 35 feet. Several large gas wells were completed on the east, or upthrown, side of the fault; and the production in the vicinity on both sides of the fault was much greater than that farther from it, amount and porosity of sand being equal.

Minor faulting exists, and the writer believes that the irregularity of contouring on top of any of the producing horizons may be partly attributed to this factor.

The gravity of the so-called "Woodbine" oil varies from 40° to 43° Bé. for the Caddo field proper; but in the Pine Island area the gravity is lower, varying from 26° to 28° Bé.

The Pine Island field is described elsewhere in this volume by A. F. Crider, in the article "Pine Island Deep Sands, Caddo Parish, Louisiana." The top of the lower marine series was encountered at 5,925 feet, beneath approximately 2,000 feet of the red shale and sand series below the 1,600 feet of upper Trinity limes and shales. The same lower Trinity marine beds were found in the deep test drilled in 1927 and early 1928 on the Bellevue structure by the Humble Oil and Refining Company *et al.*

The Hosston area north of Caddo proper is an elongate anticline, the axis of which extends northeast and southwest, and the southwestern end of which joins the Caddo producing area. Production is obtained from the Nacatoch in the form of heavy oil of 20.5° Bé. gravity, with gas on the crest of the fold. A syncline, separating the Hosston area from Caddo on the southeast, has approximately 200 feet closure on the Nacatoch. From the bottom of the syncline the formations rise southward to the Pine Island district, where the Nacatoch is encountered at approximately the same depth as at Hosston. The largest wells had initial production as large as 500 barrels per day.

PRODUCTION STATISTICS

The figures in Table III on production statistics (1909–1927) were secured from the Louisiana State Department of Conservation and the U. S. Bureau of Mines. Production figures prior to 1909 have been added.

Altogether 114,548,365 barrels of oil have been produced from the Caddo area up to the year 1928, with only a very small percentage of the total coming from sands other than the "Woodbine" horizon. In completely developed areas, the average recovery per acre is approximately 5,000 barrels, although the per-acre recovery from some leases, not typical of the whole, has been as large as 30,000 barrels.

SUMMARY

The Caddo field is a large, low anticline on the northern end of the Sabine uplift. The structure is modified by local folds, most of which have axes at right angles to the axis of the main uplift. Many faults influence the amount of production and are generally parallel with the axis of the main uplift or parallel with the axes of the cross folds.

Upper Cretaceous sediments were unconformably deposited on the eroded surface of Comanche strata, which had been previously folded,

TABLE III

CADDO PARISH PRODUCTION (INCLUDING CADDO, HOSSTON, AND PINE ISLAND)

Year	Barrels	Year	Barrels
1906	20,358	1918	11,143,890
1907	50,000	1919	9,239,829
1908	499,931	1920	6,252,795
1909	1,028,818	1921	5,391,166
1910	5,090,793	1922	4,231,555
1911	6,995,828	1923	3,998,593
1912	7,117,949	1924	4,251,319
1913	9,781,560	1925	4,087,673
1914	7,572,254	1926	4,669,421
1915	6,471,879	1927	5,703,434
1916	5,463,682	1928*	4,924,605
1917	5,483,638		

* 1928 figure added since this paper was written.—EDITOR.

elevated, and eroded. Thus at Pine Island, the peak of the Comanche "high," Trinity beds are found immediately below the Upper Cretaceous sediments, although on the western edge of Caddo 1,600 or more feet of Washita and Fredericksburg strata lie between the Upper Cretaceous and Trinity rocks.

Several movements have occurred subsequent to the deposition of the Upper Cretaceous, with resultant unconformities, the most important of which is post-Claiborne in age.

The most prolific horizon of the Caddo field has been the so-called "Woodbine." It has been neither proved nor disproved that part of this horizon is Woodbine in age, but it is here contended that part of it is Tokio in age, part a laterite occurring in the unconformity between the Upper and Lower Cretaceous, and part Washita in age.

HOMER OIL FIELD, CLAIBORNE PARISH, LOUISIANA[1]

W. C. SPOONER[2]
Shreveport, Louisiana

ABSTRACT

The Homer field, discovered in 1919, has produced more than 56,000,000 barrels of oil to date, and it is estimated that the ultimate production will total 64,000,000 barrels. Expressed in terms of acre yield, the production to date has been 24,600 barrels per acre, and the ultimate production is estimated at 28,000 barrels per acre.

The Homer dome has a diameter of about 9 miles and a structural relief of 1,100 feet. The producing area comprises 2,300 acres at the apex of the dome. The dome is traversed by an east-west trending fault of the normal type, with the downthrow toward the south. The maximum throw of more than 500 feet coincides with the highest part of the dome. The angle of the fault plane ranges from 40° to 50°.

The oil is obtained from two sands in the Gulf series of the Cretaceous. The Nacatoch sand is productive throughout the field at depths ranging from 675 to 1,150 feet below sea-level. The Oakes sand produces oil on the south side and salt water on the north side of the major fault. The depth of the oil-producing sand ranges from 1,750 to 1,850 feet below sea-level. This erratic distribution of the oil in the Oakes sand is ascribed to upward migration along the fault plane, whereby the oil, which under normal conditions would have been trapped in the Oakes sand on the north side of the fault, migrated upward into the Nacatoch sand on either side of the fault.

The Trinity group of the Comanche series has not been tested in this area but is believed to contain promising oil- and gas-producing horizons.

Introduction

The Homer field, discovered in 1919, has been the most prolific, and, because of the high price obtained for the greater part of the oil produced, the most profitable of the northern Louisiana oil fields. In addition to the economic aspects it presents geologic features of more than ordinary interest, which are presented in summary form in this paper.

Location and Extent of Field

The Homer field comprises 2,300 acres in T. 21 N., R. 7 W., and T. 21 N., R. 8 W., Claiborne Parish. The nearest producing fields in Louisiana are: the Haynesville field, 12 miles north; the Cotton Valley field, a like distance west; and the Monroe gas field, 40 miles east. The field is situated north of the region of interior salt domes, 18 miles from the Vacherie salt dome.

[1] Manuscript received by the editor, June 26, 1928.

[2] Consulting geologist, Ardis Building.

Acknowledgments

The oil companies and individual geologists of the section have generously contributed data which the writer gratefully acknowledges. He is especially indebted to S. C. Stathers for such data, and to Roy T. Hazzard for assistance in the field work and for the construction of the production curves that accompany this paper.

History

According to the best available information, it was in 1916 that A. E. Wilder, acting upon the recommendation of John Y. Snyder, leased 30,000 acres of land that included most of the producing area of the Homer field.

In November, 1916, Wilder assigned 15,000 acres to the Atlas Oil Company, now the Palmer Corporation, for the consideration of a well, drilling to begin before February 2, 1917. A. E. Hartman, geologist for the Atlas Oil Company, examined the area and recommended a location in Sec. 20, T. 21 N., R. 7 W., for the first test well. Hartman left the company before drilling commenced, and for some reason the location was changed to Sec. 22, T. 21 N., R. 7 W. This well, known as the Atlas Oil Company's Moore No. 1, was abandoned as a dry hole at a total depth of 2,910 feet.

In August, 1917, the Atlas Oil Company assigned to T. F. Denman and A. F. Williams two blocks of leases, one of 3,753 acres and the other of 3,879 acres. The consideration was the drilling of a well on each block. In November of the same year The Consolidated Progressive Oil Company assumed the fulfilment of Denman and Williams' contract with the Atlas Oil Company. The first well drilled under this contract was the Featherstone No. 1, in SW. ¼, Sec. 20, T. 21 N., R. 7 W. Hartman's original location. It was junked at a depth of 2,287 feet after yielding a showing of oil. The second, and discovery, well was drilled on the Shaw farm in the southwest corner, NW. ¼, NE. ¼, Sec. 30, T. 21 N., R. 7 W. It came in, January 12, 1919, making 2,500 barrels of oil and water from the Nacatoch sand, from 1,409 to 1,416 feet.

The first well completed in the north field was the Standard Oil Company's Lowenberg No. 1 in the southeast corner, NE. ¼, NE. ¼, Sec. 24, T. 21 N., R. 8 W. It was completed June 30, 1919, producing 150 barrels from the Nacatoch sand at a depth of 1,160 feet.

The second sand (Oakes sand) was discovered with the completion of the Standard Oil Company's Guy Oakes No. 1 well in the northwest corner, SW. ¼, Sec. 29, T. 21 N., R. 7 W. It was completed October 10, 1920, with a production of 20,000 barrels from a depth of 2,090 feet.

tion crops out in a small window adjacent to the fault in the southwest corner, NW. $\frac{1}{4}$, Sec. 19, T. 21 N., R. 7 W. It consists of light-colored and reddish sand with interbedded thin lenses and partings of ferruginous sandstone.

Cane River formation.—The Cane River formation, basal Claiborne, forms a crescent-shaped band ranging from 100 to 300 feet in width which

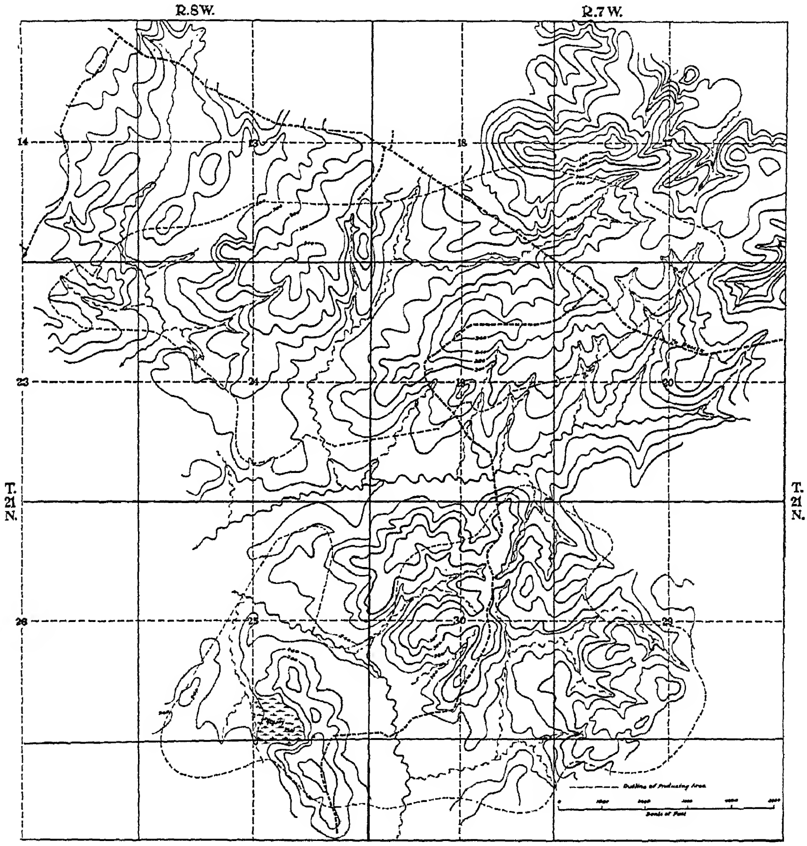


FIG. 1.—Topographic map of the Homer field. Contour interval, 20 feet.

encircles the Wilcox formation on the north. It is made up of glauconitic sand and clay characterized by round sand concretions 1–4 inches in diameter. The concretions have a shell $\frac{1}{4}$–$\frac{1}{2}$ inch thick, and some are filled with glauconite and glauconitic sand and others with red clay. The formation is sparingly fossiliferous. It has a thickness of 75 feet.

TABLE I

GENERALIZED SECTION OF FORMATIONS IN THE HOMER FIELD

System	Series	Group	Formation	Thickness (in Feet)	Character
Tertiary	Plio-cene(?)		Superficial gravels	0–2	
	Eocene	Claiborne	St. Maurice	0–300	Mainly sands with some interbedded ferruginous clay and sandstone. Some glauconite. Sparingly fossiliferous
			Sparta sand	400–450	Massive reddish and light-colored sands with stringers, thin beds, and nodules of white clay and platy ferruginous sandstone. Non-fossiliferous
			Cane River	75	Glauconitic sands and some chocolate-colored clays. Siderite concretions. Fossiliferous
			Wilcox	400–600	Lignitic sands and clays
			Midway	450±	Non-calcareous gray and dark clays in upper part. Fossiliferous dark clay in basal part. Siderite concretions
		Unconformity			
Cretaceous	Gulf	Navarro	Arkadelphia clays	90–125	Dark-colored clays with some chalk in the lower half. Fossiliferous
			Nacatoch sand	250	Sand, sandy limestone with shale at the base. Fossiliferous (Oil-producing horizon)
			Saratoga chalk	80–100	Hard white and gray chalk. Fossiliferous
		Taylor	Marlbrook marl	125	Light-colored chalky shale and marl. Fossiliferous
			Annona chalk	100	Hard white chalk. Fossiliferous
			Ozan (Oakes sand at the base 50–60 feet)	275	Gray calcareous shale with 50–60 feet of sand at the base. (Oil-producing horizon)
			Brownstown marl (200 feet)		Mainly fine-grained gray and bluish-green and green sands, grayish-green and gray fine sandy shales and gray and greenish-gray clays—in part lignite. Entire section silty. Considerable volcanic ash
		Austin	Tokio (450 feet)	650	
			Woodbine sand		Doubtfully present in the lower 30 feet of beds
		Unconformity			
	Comanche	Trinity	Upper Glen Rose	850	Red and brown clay and shale. Argillaceous limestone, gray and black shale, and sandy shale. Thin beds of fine-textured sand and sandstone
			Anhydrite zone	500	Anhydrite interbedded with limestone
			Lower Glen Rose		Chiefly calcareous and non-calcareous gray to black shale and argillaceous limestone. Some red and brown shale, and lenses of very fine-textured sand and sandstone
			Red sand and shale zone	1,800±	Red and brown shale and clay. White, gray, and red sand and sandstone

Sparta sand.—The Sparta sand is at the surface of the greater part of the producing area of the Homer field except for a band of the St. Maurice formation adjacent to the fault on the south side. It is made up of massive, generally reddish sand, with thin stringers and nodules of white clay and, in places, thin platy ferruginous partings. The upper part of the formation contains thin beds of light-colored clays and some thin-bedded ferruginous sandstone. The Sparta sand ranges from 400 to 450 feet in thickness.

St. Maurice formation.—The lower part of this formation is exposed in the hills encircling the producing area of the field and in a band contiguous with the south side of the major fault. It consists principally of ferruginous clay and sand and ferruginous sandstone. The clays in places contain concretions and beds of limonite in which are found casts of marine invertebrate fossils. The beds are sparingly glauconitic. The total thickness of the St. Maurice is slightly more than 300 feet in this area.

Surficial deposits.—In several localities in the Homer field are irregularly distributed patches of gravel which have no obvious relationship to the streams of this area. Most of these deposits consist of unconsolidated gravel made up mainly of chert pebbles, but a few boulder-like masses of conglomerate are found. The conglomerate consists of chert pebbles in a matrix of ferruginous sand. There is no accordance in the levels at which the gravels occur, and they are probably the residuum of a former high-level terrace.

The age of the gravels has not been determined, but it is believed that they were deposited upon a peneplain developed during the Pliocene epoch.

SUBSURFACE FORMATIONS

COMANCHE SERIES (LOWER CRETACEOUS)

There is little information concerning the Comanche series underlying the producing area of the Homer field, as few wells have reached these beds, and only one well, Standard Oil Company's Shaw No. 50 in Sec. 30, T. 21 N., R. 7 W., has penetrated them for any considerable distance. This well records 700 feet of beds, mainly limestones, that are assigned to the Trinity group, but, as no information other than the driller's log is available, their position in the geologic column is not determinable.

The most complete section of this area is obtained from the Magnolia Petroleum Company's C. C. Lee No. 1, in Sec. 16, T. 22 N., R. 8 W., the extreme northern margin of the Homer dome. This well penetrated nearly 1,600 feet of beds of the Trinity group. (See section, Fig. 2.)

The Gulf series is separated from the Comanche series by the most pronounced unconformity that has been recognized in the Mesozoic of this region. The sequence of events preceding the deposition of the Gulf series is imperfectly known but, according to our present understanding, was briefly as follows. At, or near, the close of the Comanche epoch the sediments were uplifted and folded, and in general tilted westward and southward. Domes of small areal extent and high structural relief, such as Bellevue[1] and Pine Island,[2] were developed at this time. The uplift was followed by a period of erosion during which the beds were truncated and the terrain reduced to a peneplain. In the region discussed in this paper, the Gulf series is in contact with the Trinity group of the Comanche series. The thickness of the upper beds of the Trinity group therefore varies according to the amount of structural relief attained prior to the deposition of the Gulf series. The amount of such deformation on the Homer dome is not determinable, but it may total several hundred feet.

TRINITY GROUP

The Trinity group is represented in this area by not less than 4,000 feet of beds made up of sand, shale, limestone, and anhydrite. The upper few hundred feet and the lower 1,800 to 2,000 feet of beds are predominantly red; the sands are generally fine-textured; the limestones, argillaceous; and much of the shale is non-calcareous.

The entire thickness of the Trinity group has not been penetrated in deep wells, although the Humble Oil and Refining Company's Bliss and Weatherbee No. 30, Bellevue field, passed through the red shale and sand zone and penetrated 500 feet of limestone and shale which, although not definitely correlated, are probably of Comanche age.

The following divisions of the Trinity group are recognized in this area: upper Glen Rose, anhydrite zone, lower Glen Rose, and red shale and sand zone.

Red shale and sand zone.—This zone has not been reached in any of the wells drilled on the Homer dome, but it probably is present. In the Bellevue field these beds had a thickness of 1,900 feet, and in southern Arkansas nearly 1,800 feet of beds of similar character have been recorded in deep wells.

In the Bellevue field this zone may be subdivided into an upper zone 1,000 feet thick and a lower zone 900 feet thick. The upper zone is made

[1] L. P. Teas, "Bellevue Oil Field, Bossier Parish, Louisiana," this volume, pp. 229–53.

[2] A. F. Crider, "Pine Island Deep Sands, Caddo Parish, Louisiana," this volume, pp. 168–82.

up of pink, red, and brown clays and shales and gray and red sands. The lower zone consists principally of white and red sands and sandstone. The same general subdivisions may be made in southern Arkansas, and probably the same will hold for the Homer area.

Lower Glen Rose.—This part of the Glen Rose was penetrated on the Bellevue dome, where 1,150 feet of limestone and shale were recorded. A deep well in the Cotton Valley field records 900 feet of beds, consisting mainly of shales, with subordinate beds of limestone and sand that are assigned to the lower Glen Rose.

These beds decrease appreciably in thickness and laterally change in character eastward from the Bellevue field. In the Cotton Valley and Haynesville fields there is a noticeable decrease of the calcareous content of the beds, and sand lentils are recorded at the several horizons. The same condition is shown in the deep well on the north flank of the Homer dome. The increase of the sand enhances the possibilities of deep production in this area.

The section given in Table II contains the deep oil-producing horizon of the Cotton Valley field (Fig. 2).

Anhydrite zone—In this zone have been included all of the beds from the top of the highest to the base of the lowest bed of anhydrite. Thus defined, it has a thickness of 500 feet, made up of massive and thin-bedded anhydrite, argillaceous limestone, and calcareous shale. Some of the limestone contains small amounts of pyrite. The anhydrite is sedimentary in origin and is, in many places in the section, interbedded with marine limestone containing what appears to be an impoverished marine fauna. Because of the distinctive and easily recognized character, the anhydrite is an excellent key horizon and should be accurately recorded when penetrated in deep wells. The section given in Table III was recorded in the Magnolia Petroleum Company's Lee No. 1 well, Sec. 16, T. 22 N., R. 8 W., the extreme northern margin of the Homer dome.

Upper Glen Rose—To this formation are tentatively assigned the 850 feet of beds above the anhydrite, which were penetrated in the deep well drilled on the extreme northern margin of the Homer dome. It should be stated, however, that in this area neither the contact between the Gulf and the Comanche series nor the age of the upper beds assigned to the Comanche series has been definitely established at this time.

On the basis of lithology the upper Glen Rose is divisible into three parts.

The lower 375 feet of beds are made up chiefly of gray and bluish-gray calcareous shale, with subordinate beds of sands, sandstone, and argil-

laceous limestone. The beds are mostly calcareous and contain microfossils and shell fragments and a few poorly preserved *Ostrea* sp. and *Pecten* sp. The sands and sandstones are very fine-textured.

TABLE II

SECTION, LOWER GLEN ROSE BEDS, MAGNOLIA PETROLEUM COMPANY'S C. C. LEE No. 1 WELL IN SEC. 16, T. 22 N., R. 8 W.

Bottom of Formation (in Feet)	Character
4,918–30	Gray, finely crystalline limestone
4,936	Very fine-textured, bluish-gray silty sand, slightly calcareous
4,942	Gray limestone
4,944	Argillaceous gray limestone, fragments of *Ostrea* sp. and *Pecten* sp.
4,948	Very fine-textured gray sand and sandstone, slightly calcareous
4,949	Dark gray argillaceous limestone, fossiliferous
4,951	Brown shale with small nodules of green shale
4,956	Fine-textured brown sandstone
4,967	Reddish-brown shale
4,973	Olive-green, slightly calcareous clay
4,977	Bluish-gray clay with some very fine-textured sand
4,986	Reddish-brown shale
4,991	Brown shale
4,996	Finely crystalline bluish-gray limestone, fossiliferous
5,002	Gray limestone, fragments of thin-shelled *Ostrea* sp.
5,008	Fine-textured gray silty sand
5,014	Gray argillaceous limestone, fossiliferous
5,019	Fine-textured gray lignitic sandstone
5,024	Fine-textured gray sand
5,029	Reddish-brown clay
5,033	Very fine-textured micaceous gray silty sandstone
5,035	Fine-textured light green sandstone
5,043	Brown clay
5,049	Very fine-textured silty gray sandstone
5,053	Gray argillaceous limestone, fossiliferous, and dark gray to black non-calcareous shale
5,057	Sandy gray limestone, sparingly fossiliferous
5,059	Very fine-textured micaceous bluish-green and green sandstone, slightly calcareous
5,068	Greenish-gray and green non-calcareous shale
5,073	Gray, finely crystalline limestone, small oölites
5,079	Gray argillaceous limestone
5,091	Olive-green clay
5,097	Bluish-gray shale, slightly calcareous
5,100	Bluish-gray non-calcareous shale

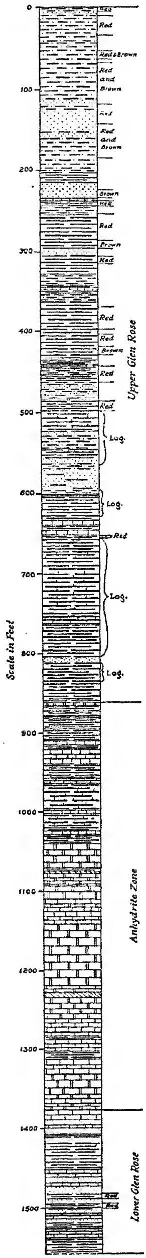


FIG. 2.—Detailed section of a part of the Trinity group of the Comanche series.

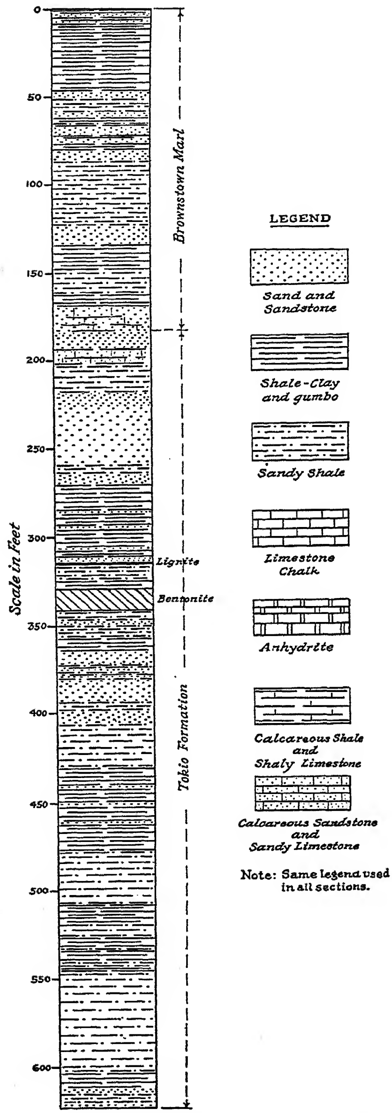


FIG. 3.—Detailed section of the Brownstown marl and the Tokio formation of the Gulf series.

TABLE III

SECTION OF ANHYDRITE ZONE IN MAGNOLIA PETROLEUM COMPANY'S C. C. LEE No. 1 WELL, SEC. 16, T. 22 N., R. 8 W.

Bottom of Formation (in Feet)	Character
4,401–05	Gray, white, and pink anhydrite
4,408	Dark gray fissile shale, fossiliferous
4,418	Calcareous gray shale
4,420	Gray limestone, shell fragments
4,432	Gray shale, slightly calcareous
4,434	White powdery calcium sulphate, slight amount of secondary calcite
4,442	Dark gray siltstone
4,454	Dark gray calcareous shale and dark gray argillaceous limestone
4,466	Light gray limestone, fossiliferous, and dark gray calcareous shale
4,480	Dark gray, fine-textured limestone, fossiliferous
4,498	Dense, dark gray shale, fossil fragments
4,505	Gray limestone, fossiliferous
4,515	Dark gray shale, fossiliferous
4,528	Gray shale
4,546	Dark gray shale and finely crystalline gray limestone, fossiliferous
4,560	Dark gray shaly limestone, shell fragments
4,570	Black shale, slightly calcareous
4,574	Dark gray argillaceous limestone
4,578	Black shale and gray-to-buff, slightly sandy limestone
4,586	White anhydrite, fractured, calcite filling along fractures
4,594	Interbedded anhydrite and fine-grained buff limestone
4,606	White and bluish-gray anhydrite
4,612	Anhydrite fragments embedded in limestone
4,614	Black shale and argillaceous gray limestone
4,618	Bluish-white anhydrite and powdery white calcium sulphate
4,624	Anhydrite with blobs and stringers of gray limestone
4,629	Anhydrite
4,634	Anhydrite and fine-textured black argillaceous limestone
4,652	White and bluish-gray anhydrite
4,658	Gray limestone with inclusions of anhydrite
4,662	Anhydrite
4,666	Fine-textured dark bluish-gray limestone
4,671	Conglomerate of limestone and anhydrite
4,677	Fine-textured dark gray argillaceous limestone and anhydrite
4,683	Anhydrite with thin stringers of gray limestone
4,695	Anhydrite with some thin stringers of dense gray-to-buff limestone
4,748	Anhydrite
4,757	Gray oölitic limestone

TABLE III—*Continued*

Bottom of Formation (in Feet)	Character
4,760	Anhydrite
4,764	Anhydrite with fine-textured gray limestone stringers $\frac{1}{2}$–$\frac{3}{4}$ inch thick
4,768	Anhydrite
4,776	White powdery calcium sulphate
4,801	Anhydrite
4,812	Finely crystalline gray limestone, shell fragments
4,819	Dark gray oölitic limestone
4,825	Gray limestone, fossiliferous
4,831	Fossiliferous gray limestone and black calcareous shale
4,837	Oölitic gray limestone and fine-textured dark gray argillaceous limestone
4,843	Gray limestone and dark gray argillaceous limestone, shell fragments
4,853	Dark gray calcareous shale, fossiliferous
4,859	Oölitic gray limestone, shell fragments
4,871	Dark gray argillaceous limestone and calcareous shale
4,875	Dark gray argillaceous limestone
4,877	White and bluish-gray anhydrite
4,880	Anhydrite and dark gray argillaceous limestone
4,886	Anhydrite and dark gray fossiliferous limestone
4,892	Anhydrite
4,898	Interbedded anhydrite and argillaceous limestone
4,904	Gray limestone with stringers of anhydrite $\frac{1}{4}$–$\frac{1}{2}$ inch in thickness
4,910	Dark gray, finely crystalline limestone, fossiliferous
4,918	Anhydrite

The intermediate 250 feet of beds are mainly red, brown, gray, and greenish-gray calcareous and non-calcareous shales, with subordinate beds of sandy shale, sand, and sandstone and thin lenses of argillaceous limestone. The sands are generally fine-textured. The section is sparingly fossiliferous.

The upper 225 feet of beds are dominantly red, brown, and gray sandy shale and fine- to medium-textured gray and green sand and sandstone and some gray and greenish-gray shale. A few micro-fossils and some shell fragments are present in these beds.

GULF SERIES (UPPER CRETACEOUS)

The Gulf series underlying northern Louisiana was first correlated by Harris,[1] who described the geology of the Caddo fields in 1910. Since that

[1] G. D. Harris, "Oil and Gas in Louisiana," *U. S. Geol. Survey Bull. 429* (1910), p. 30.

time a vast amount of information has become available which has enabled the workers in this district to revise the correlation to correspond with the revised section of the Gulf series in southwestern Arkansas established by Dane.[1] Table IV gives the correlation of the earlier and the revised section of this district.

Woodbine sand.—This formation is recognized in wells drilled in southern Arkansas, where it consists of sand in a matrix of volcanic material. It has not been recognized in the Homer field.

TABLE IV

CORRELATION OF UPPER CRETACEOUS IN LOUISIANA

System	Series	G. D. Harris, *U. S. Geol. Survey Bull. 429* (1910)		This Paper	
		Group	Formation	Formation	Group
Cretaceous Upper	Gulf		Arkadelphia clay	Arkadelphia clay	Navarro
			Nacatoch sand	Nacatoch sand	
			Marlbrook marl, including Saratoga chalk member	Saratoga chalk	
				Marlbrook marl	Taylor
		Austin	Annona chalk	Annona chalk	
			Brownstown marl	Ozan formation with Oakes sand at base	
			Eagle Ford clays (Blossom sand member at the top)	Brownstown marl	
				Tokio formation	Austin
			Woodbine sand	Woodbine sand	

Tokio formation and Brownstown marl.—The Tokio formation of the Austin group and the Brownstown marl of the Taylor group are not easily differentiated in this area. They have a combined thickness of 650 feet, of which 450 feet is perhaps assignable to the Tokio formation and 200 feet to the Brownstown marl (Fig. 3).

Tokio formation.—The formation is made up of gray sandy shale and shale; gray and pale green sand and sandstone. The shales are, for the most part, non-calcareous and, in part, lignitic. The sands and sandstones are fine to medium in texture and contain considerable volcanic

[1] C. H. Dane, *U. S. Geol. Survey Press Bull. 8823* (September 10, 1926).

material as a matrix as well as some fine-grained glauconite. In addition to the disseminated volcanic material there is a bed of water-laid volcanic material ranging from 8 to 10 feet in thickness. The calcareous shales generally contain micro-fossils.

Brownstown marl.—The Brownstown marl consists of calcareous gray sandy shale and shale and gray sand and sandstone. The sands are in part calcareous and contain some glauconite.

Ozan formation.—The upper 200 feet of the Ozan formation consists of gray and bluish-gray calcareous shale and fine sandy shale. The lower 50–60 feet of beds is the Oakes sand, the second oil-producing horizon of the Homer field.

Annona chalk.—To this formation are assigned 100 feet of hard white and gray chalk with subordinate beds of chalky shale.

Marlbrook marl.—In the Marlbrook marl are included the clays and marls between the top of the Annona chalk and the base of the Saratoga chalk. It is made up of light-colored chalky clay and marl. Its average thickness as recorded in wells is 125 feet.

Saratoga chalk.—The Saratoga chalk consists of 80–100 feet of white and gray chalk, with intercalated thin beds of chalky shale.

Nacatoch sand.—The Nacatoch sand is made up of an upper sand and sandy limestone member ranging from 150 to 175 feet in thickness, and a lower shale member ranging from 75 to 100 feet in thickness. It is the main oil-producing horizon of the Homer field. The producing sand is discussed in a later paragraph.

Arkadelphia clay.—In the well records the Arkadelphia clay is not easily separated from the overlying Midway clays of Eocene age. In the Homer area 90 to 125 feet of black shale and clay, and considerable chalk in the lower 50 feet, are assigned to the Arkadelphia clay.

TERTIARY

Midway formation.—The lower 50–75 feet of the Midway formation consists of calcareous gray and dark gray clay containing a plentiful micro-fauna. The remainder of the formation consists of gray and dark gray non-calcareous clay. It is characterized by numerous siderite concretions, and is commonly logged by the drillers as shale and boulders. The thickness of the Midway formation ranges from 450 to 500 feet.

Wilcox formation.—The Wilcox formation appears at the surface in a small window adjacent to the fault in the southwest corner, NW. $\frac{1}{4}$, Sec. 19, T. 21 N., R. 7 W., where 50–60 feet of light reddish sand interbedded with thin lenses of ferruginous sandstone are exposed.

As shown in the drillers' logs, it is composed chiefly of sand and sandy shale, with subordinate beds of shale and clay. Much disseminated lignitic matter is present throughout the formation, and some beds of lignite occur. The Wilcox is approximately 400 feet thick in the producing area but increases to nearly 600 feet on the southern margin of the dome.

PRODUCING HORIZONS

Production in the Homer field is obtained from two sands, both in the Gulf series. The upper, Nacatoch sand, produces throughout the field but is most prolific in the north field. The second, Oakes (Blossom) sand, produces oil in the south field, which is on the downthrown side of the major fault, and salt water in the north field.

With few exceptions, the wells in the field were drilled and completed with rotary tools, and the records of the producing horizons are not as accurate as could be desired. The more detailed section of the Oakes sand is obtained from a well on the north flank of the Homer dome, but, as this horizon persists throughout a wide area without any appreciable change in character, it accurately represents the conditions within the producing area of the field.

NACATOCH SAND

In the north field the Nacatoch sand produces from depths ranging from 675 to 1,100 feet below sea-level. In the south field, which is on the downthrown side of the major fault, the producing depths range from 1,050 to 1,150 feet below sea-level.

The Nacatoch sand, as previously defined, consists of two members: an upper sand member 150 feet in thickness, and a lower shale member 100 feet in thickness. The oil-producing sands are in the upper member.

NORTH FIELD

The principal producing member of the Nacatoch sand is within the upper 50 feet of beds, although oil is obtained from several thin beds and lenses in the lower 100 feet of the sand member. The actual thickness of the upper producing members differs greatly from place to place in the field, its thickness probably depending upon the completeness of the secondary cementation of the sand. The lower 100 feet of the sand member is composed chiefly of calcareous sandstone and sandy limestone, with irregularly distributed lenses and thin beds of soft sand, and a sand at the base ranging from 5 to 10 feet in thickness. The thin beds produce some oil, and the basal sand is an important producing member in this field.

SOUTH FIELD

The Nacatoch sand in this part of the field is essentially the same as in the north field, with the exception that the calcareous content is considerably greater and the porosity correspondingly lower. In this field, as in the north field, the main producing horizon is in the upper 50 feet of beds, and the sand at the base of the upper member is generally water-bearing.

As no cores of the Nacatoch sand are available, it is not easily determined whether the smaller yield per well and per acre in the south field is due to vagaries in the accumulation of the oil or to the effect of secondary cementation. The latter is, in the writer's opinion, the principal reason, as the production from offset wells equally well located with reference to structure shows variations that can scarcely be attributed to other causes.

In general appearance the producing sand is a medium- to fine-textured sand, commonly described as salt-and-pepper sand. It is a poorly cemented calcareous sand, slightly argillaceous, and in part glauconitic. The quartz grains are medium- to fine-textured and angular. Grains with well-rounded corners are negligible. No accurate data are available concerning the porosity.

A typical well record of the Nacatoch sand in a well completed with cable tools is given in Table V.

TABLE V

SECTION OF NACATOCH SAND IN ARKANSAS NATURAL GAS COMPANY'S LANGSTON No. 94, SEC. 24, T. 21 N., R. 8 W.

Bottom of Formation (in Feet)	Character	
993–1,005	Gray sand..	Oil
1,008	Sand.......	
1,120	Sand and hard lime	
1,122	Sand............	Oil

OAKES SAND

The Oakes sand, named after the Oakes farm, upon which the discovery well was drilled, is also known as the "Blossom" and the "Haynesville" sand. Stratigraphically it is, as far as can be determined, the equivalent of the Buckrange sand of southwestern Arkansas.

The thickness of the Oakes sand ranges from 50 to 60 feet. It is fine to coarse sand and sandstone, with a considerable admixture of volcanic material and some glauconite, which determines the prevalent green color of these beds. The upper part of the section contains pebbles of novaculite

and igneous rocks, accounting for the high porosity of the producing horizons in the Homer field, which have yielded wells with an initial daily production of 40,000 barrels. A detailed section of the Oakes sand is shown in Figure 4.

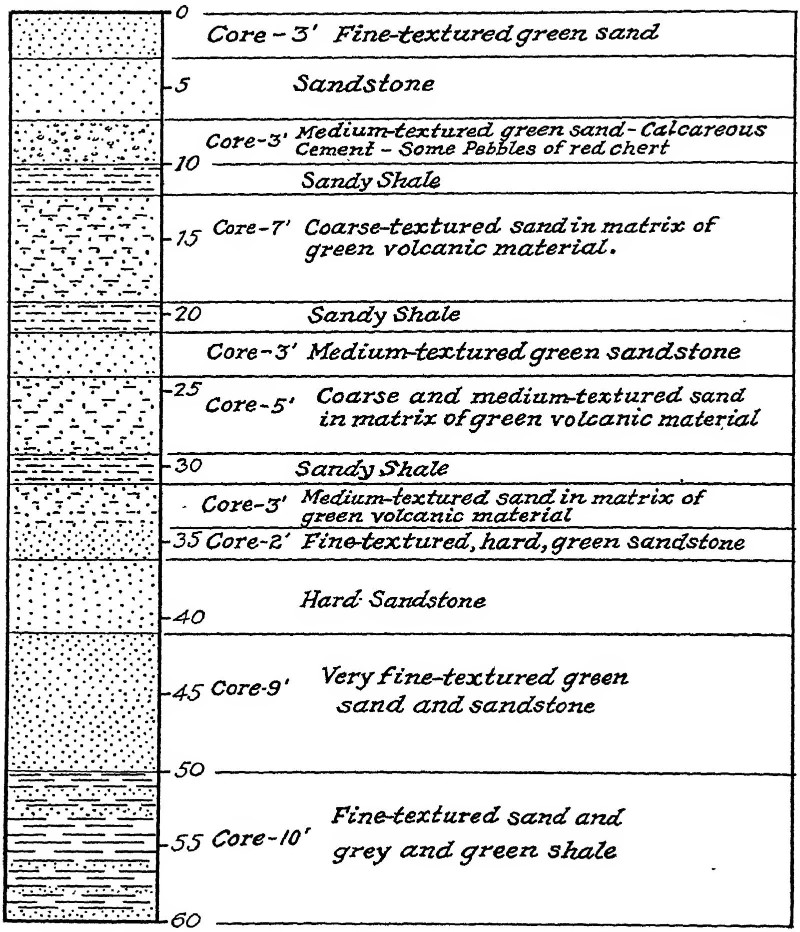


FIG. 4.—Detailed section of the Oakes sand. Depth and thickness of cores shown in feet. Unless noted as cored, lithology is taken from driller's log.

STRUCTURE

SURFACE STRUCTURE

The main structural features of the Homer dome are clearly shown in the distribution and attitude of the outcropping rocks (Fig. 5). The

main fault that traverses the dome from east to west can be traced, with slight interruptions, from Sec. 14, T. 21 N., R. 8 W., to Sec. 16, T. 21 N., R. 7 W. The highest part of the dome is in the southwest corner, NW. $\frac{1}{4}$, Sec. 19, T. 21 N., R. 7 W. It is marked by a small window of the Wilcox

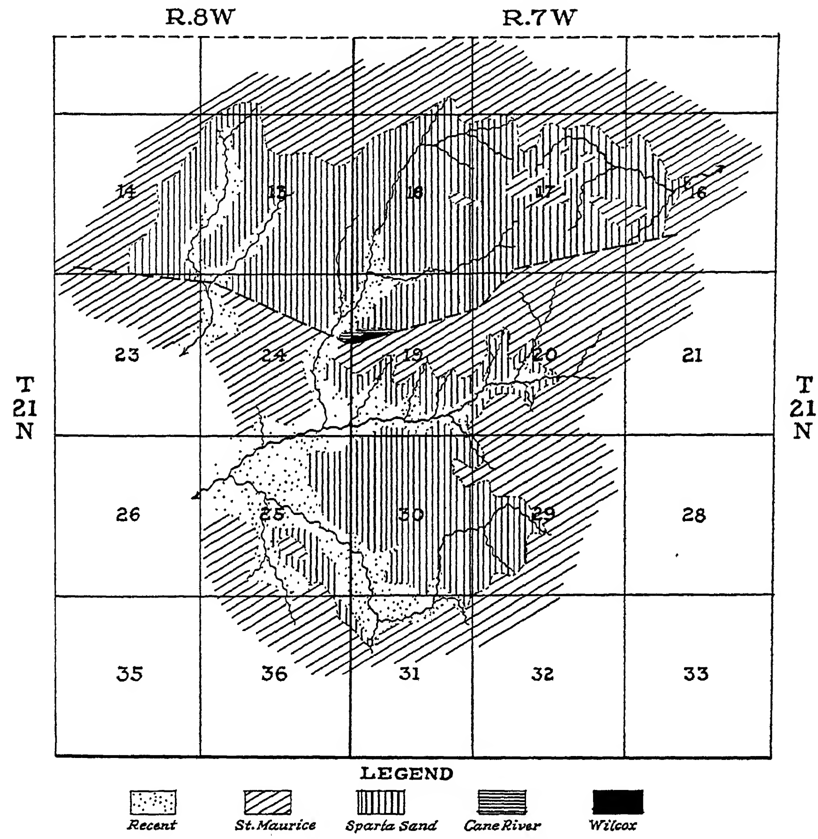


FIG. 5.—Areal geology of the Homer field.

formation that on the south side is in contact with the St. Maurice formation. On the north side, the Wilcox is separated from the Sparta sand by a narrow band of the Cane River formation. The Sparta sand crops out in the center of the dome throughout an area 2–2½ miles in diameter, except as previously noted, and with the exception of a narrow band of the St. Maurice formation that parallels the fault on the downthrown side. The Sparta sand is encircled by the St. Maurice formation, which is

normally at the surface in this area. Dips corresponding closely to the dip of the Nacatoch sand can be observed in many localities. The band of the St. Maurice formation that parallels the fault on the downthrown

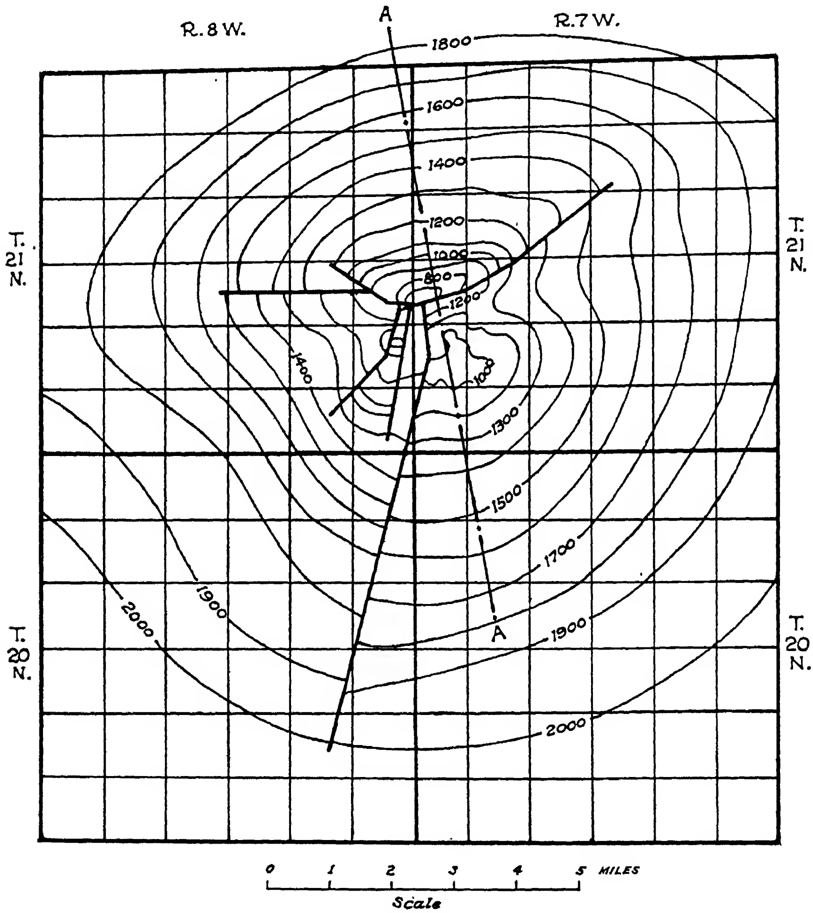


FIG. 6.—Generalized geologic structure map of the Homer dome. Contours drawn on the top of the Nacatoch sand showing depths below sea-level. Width of area mapped, approximately 12 miles.

side is inclined toward the fault plane at angles ranging from 5° to 20°. The calculated vertical relief, based on the measured thickness of the exposed beds, is in substantial agreement with the relief determined in the Nacatoch sand.

SUBSURFACE STRUCTURE

Figure 6 is a generalized structure map of the Homer dome, drawn on the top of the Nacatoch sand at intervals of 100 feet. As comparatively few wells have been drilled outside of the producing area, it follows that the structure is somewhat generalized on the outer margin of the dome.

This dome is nearly circular in outline, with a diameter of slightly more than 8 miles at the base of the lowest closing contour line. The maximum structural relief is 1,100 feet (Fig. 7). The average dip is 2.5°

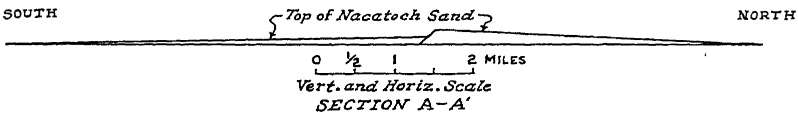


FIG. 7.—Section *A-A'*. Showing relation between vertical relief and diameter of the dome.

on the south flank and 3° on the north flank. The dome is traversed by a major fault with an irregular but generally east-west trend. The maximum throw of the fault is 500 feet and coincides with the highest part of the dome. The amount of throw decreases away from the apex of the dome. The fault is of the normal type, with the downthrow on the south, and the angle of the fault plane with the horizontal ranges from 40° to 50°. The downthrown side of the dome is traversed by several minor radial faults which have their loci near the apex of the dome. They have small horizontal extent, and the amount of throw in no place exceeds 100 feet.

The generally east-west trending fault divides the Homer field into two separate and distinct producing areas, which for convenience are called the "north" and "south" fields. The detailed subsurface structure map (Fig. 8) is drawn on the top of the main producing horizon of the Nacatoch sand, which ranges from 10 to 20 feet below the top of this formation.

The productive area is higher than the 1,175-foot contour which encloses an area about 3 miles in diameter. Because of local faulting and minor structural irregularities, a part only of the area enclosed by this contour is productive in the south field.

NORTH FIELD

The highest part of this area, as well as of the Homer dome, is adjacent to the fault in Sec. 19, T. 21 N., R. 7 W., and Sec. 24, T. 21 N., R. 8 W., where the depth of the Nacatoch sand ranges from 675 to 700 feet below sea-level. Outward to the margin of the producing area the dip

is nearly constant at the rate of 500 feet per mile. The influence of the fault upon the form of the dome is evidenced in the sharp influxing of the contours toward the fault in which they terminate. The total structural relief of the producing area is 500 feet. In the extreme western end of the producing area, minor faults, branching off from the main fault, have slightly modified the distribution of oil.

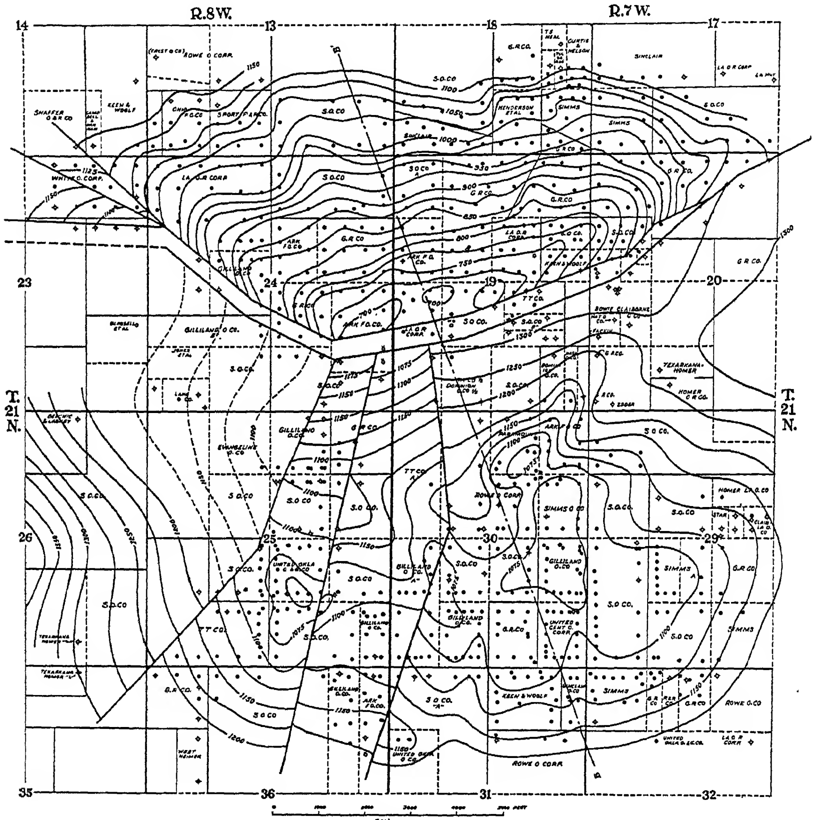


FIG. 8.—Detailed geologic structure map of the Homer field. Contours drawn on top of the Nacatoch sand, in feet below sea-level.

SOUTH FIELD

The south field is divided into several segments by south and southwest trending radial faults. The highest parts of the field are in Sec. 30, T. 21 N., R. 7 W., and Sec. 25, T. 21 N., R. 8 W., where the depth of the Nacatoch ranges from 1,050 to 1,075 feet below sea-level. The highest

points coincide with local domes of low relief developed on the generally flat surface of the producing area. The dips are low within the field, but become very steep within a short distance outward from the 1,200-foot contour. The radial faults have scarcely affected the distribution of the oil.

FAULTS

The faults of the Homer dome, viewed in plan and without regard to their relative magnitude, form an interesting radial pattern. Actually they consist of one major east-west fault and several minor faults of relatively slight importance.

The major fault is shown in the accompanying illustrations by a series of connected straight lines, which, if detailed data were available, would no doubt be somewhat modified. It has not been possible to determine whether the straight lines are slightly offset from one another or connected in a gently curving line.

The fault is of the normal type, with the downthrow toward the south. The maximum throw of 500 feet coincides with the apex of the dome, and the throw decreases outward from this point. One of the interesting features of this fault is the inclination of the fault plane, which has been determined with some degree of accuracy in several places along its extent. The dip of the fault plane ranges from 40° to 50° S. Another feature of interest is that the beds on the downthrown side do not show evidence of normal drag, but, on the contrary, are dipping into the fault plane at angles ranging from 4° to 18°.

The surface trace of the fault is most easily determined from the distribution of the surface formation, but for a considerable distance it is marked by a bed of ferruginous sandstone ranging from 1 foot to 4 feet in thickness. The sand, aside from the ferruginous content, is identical with the Sparta sand, of which it is a part, and is the result of water circulation along the fault plane.

The characteristics of the minor faults are perhaps best shown in Figure 9. Their throw is small, rarely exceeding 50 feet. They are normal faults; the relative movement of the segments is up and down with reference to one another. The fault planes are nearly vertical.

Age of Folding and Faulting

The uplift of the Homer dome, as well as other structural features of the region, was coincident with a general elevation of northern Louisiana and southern Arkansas. The uplift involved all of the Eocene and probably the Oligocene, thus placing the event in the Miocene. The uplift

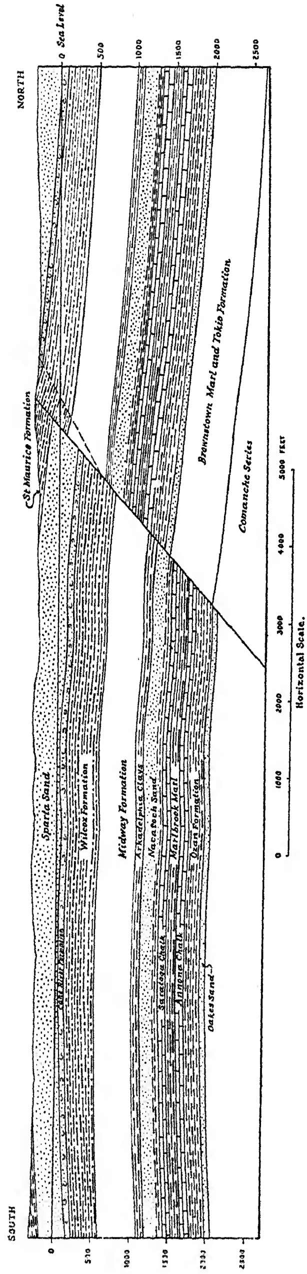


FIG. 9.—Section *B-B'* (FIG. 8). Cross section of the Homer field. Depths shown in feet.

was perhaps genetically related to the down-warping of the trough in which was deposited the great thickness of sediments represented by the Catahoula sandstone and the Hattiesburg and Pascagoula clays.

The foregoing statement applies to the Gulf series and younger sediments, but the pronounced unconformity that separates the Comanche and the Gulf series marks an earlier period of deformation which profoundly affected the attitude of the Comanche sediments. According to our present imperfect understanding of the history of the Comanche series, the sediments were uplifted and folded at or near the close of the epoch. Locally, domes of small areal extent, but with a structural relief of 800 to 1,500 feet, were developed at this time. In the subsequent interval of erosion, between the end of the Comanche epoch and the deposition of the basal beds of the Gulf series, the beds were truncated and the terrain reduced to a peneplain.

Inasmuch as the structure of the Comanche strata is not known under the Homer dome, it may be profitable to examine the structure of the Bellevue dome, where more complete data are available. This dome, in so far as it concerns the post-Comanche folding, is analogous to the Homer dome.

Briefly summarized, the Bellevue dome is a nearly circular dome with a diameter of 8 miles and a structural relief of 600 feet based on the Nacatoch sand. The structural relief of the Comanche strata is not less than 1,500

feet, which represents the thickness of the beds removed by erosion prior to the deposition of the Gulf series. The localization of the uplifts is closely concordant in the Comanche and the younger strata.

Although the Comanche beds penetrated in the Standard Oil Company's Shaw No. 50 well, in Sec. 30, T. 21 N., R. 7 W., cannot be correlated, there can be little doubt that the Homer dome suffered considerable deformation prior to the deposition of the Gulf series; that, in fact, the dome is the result of two distinct periods of deformation.

The origin of the Homer dome and its attendant structural features is an interesting subject, which, together with the regional deformation, merits more space than the scope of this paper permits.

A knowledge of the structure of the underlying Comanche strata and its influence upon the localization and form of the dome developed in the younger sediments is an important factor, without which no discussion of the origin is complete. On the basis of comparison with conditions as known on the Bellevue and the Pine Island domes and the meager data available from this area, it may be permissible to infer that the Comanche strata are more intensely folded than the overlying younger beds and that the deformation in the younger beds is essentially concordant with the deformation of the Comanche strata. In effect, therefore, the later movement was simply a recurrent movement, and the factors involved in the uplift were essentially the same throughout the development of the dome.

The Homer dome is so obviously the result of vertically operating forces that further qualification of that statement is scarcely necessary. That the dome is at the nodal point of intersecting folds has been suggested as an alternate hypothesis but is not in accord with the evidence concerning either local or regional folding.

The Homer dome has perhaps most generally been considered as a salt dome on a grand scale, produced by a deeply buried salt intrusion. This opinion seems to have been fostered by the superficial similarity to the salt dome structure and its nearness to the salt dome region of northern Louisiana. Its comparatively great size makes it necessary to postulate a great body of salt whose presence on the margin of the salt basin would be difficult to explain. Igneous rock is equally competent to produce the results attained, and the fact that no igneous rock is present at the surface or has been penetrated in deep wells in this region does not detract from its competency. Plutonic rocks are not known to have been intruded in the Gulf series or later formations, but there is much evidence to show that there were igneous activities during the Comanche epoch.

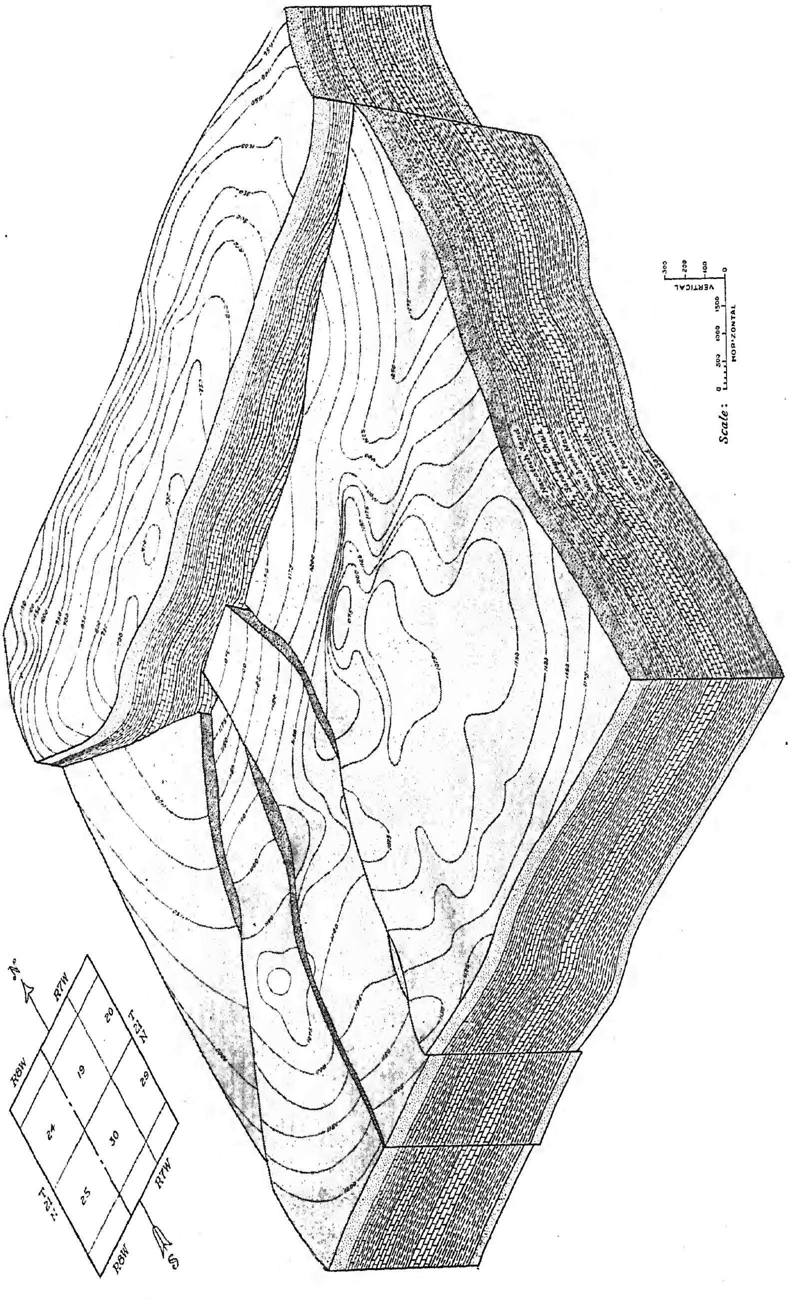


FIG. 10.—Isometric projection of the Homer field. Subsurface structure contours on the top of the Nacatoch sand below sea-level. Scale in feet.

The plutonic rocks along the margin of the coastal plain of Arkansas were intruded in the Comanche strata, and igneous rocks have been penetrated in deep wells in Arkansas and eastern Louisiana. Geophysical surveys give indications that buried bodies of igneous rocks underlie the surface in several localities in southeastern Arkansas and northeastern Louisiana. Granted that the igneous masses are nearer the surface on the east, there is nevertheless no reason why more deeply buried masses should not have intruded the Comanche strata in the area.

Considering the deformation of the Gulf series and later formations, the following sequence of events is in accord with the available evidence. The initial stage in the development of the dome was the upwarping of the strata, with resultant tensional stresses. The initial failure occurred after an indeterminate amount of vertical relief had been attained. The relief, however, was obviously not more than 600 feet, which is the difference between the throw of the fault and the maximum vertical relief of the dome. After the initial failure the upward movement continued, with the downthrown side lagging behind with reference to the upthrown side. We may consider that this movement continued until the upthrown side had reached its maximum elevation, when, because of inability to overcome friction along the fault plane at depth, the shifting of the center of application of the intrusive medium, or other factors, it came to rest. The downthrown side continued to move, as is evidenced by the sharp flexing of the strata toward the fault plane, indicating a rotational movement that could have been accomplished only by an acceleration of the movement on the downthrown side. The possibility that the relative rate of movements varied during the uplift could also have brought about these conditions.

The radial faults, which are limited to the downthrown side, suggest an acceleration of the movement of the downthrown side toward the culmination of the movement, rather than differential movement of the beds on opposite sides of the fault during the uplift.

Relationship of Oil Accumulation to Structure

The oil accumulation of the Homer field is normal to the structure in that it occupies the highest part of the dome. The Nacatoch sand produces oil throughout the field from the 1,150-foot contour to the apex of the dome. The Oakes sand produces oil within the same structural limits on the south side, and salt water on the north side of the major fault.

The distribution of the oil is ascribed to upward migration along the fault plane, whereby the oil, which under normal conditions would have

been concentrated in the Oakes sand, migrated upward into the Nacatoch sand on either side of the fault.

There is no definite proof that the Homer oil is indigenous to the Oakes ("Blossom") sand, but the relationship is strongly suggested by the facts that its properties and gravity are the same throughout the field, whether obtained from the Nacatoch or the Oakes sand, and that it is essentially similar in properties to the oil obtained from the "Blossom" sand in the Cotton Valley and Haynesville fields. The Nacatoch sand is water-bearing in the last-named fields. The properties of the Homer crude are totally different from those of the oil produced from the Nacatoch sand in other areas in northern Louisiana.

In relation to the migration, it is significant to note that there is no gas produced in the Homer field except the normal casing-head gas, and that there is no noticeable difference in the properties, gravity, or temperature of the oil produced from wells adjacent to the fault or from wells along the fault plane.

The uplift of the dome and the resultant faulting produced the conditions that permitted the upward escape of the oil. It is assumed that the Homer dome, as outlined in an earlier paragraph, had its origin in the intrusion of some competent medium, probably rock salt or igneous rock; that the dome was elevated, perhaps several hundred feet, before failure resulted; and that after the initial failure the fault developed its maximum throw as the uplift proceeded to completion. In the development of the structure, therefore, the oil-bearing Oakes sand, on the upthrown side, was successively brought into contact with the Annona chalk, the Saratoga chalk, and the Nacatoch sand on the downthrown side of the fault. The chalks are no doubt highly fractured contiguous to the fault plane, which condition facilitated the upward movement of the oil.

The character of the beds brought into juxtaposition with the oil-bearing sand is believed to be the principal factor, and water circulation and escaping gas contributory factors, in the upward migration of the oil.

The upward migration of the oil seems to have been effectively arrested by the Arkadelphia and Midway clays. Showings of oil were encountered in the Wilcox sand on the south side of the fault, and were tested in several wells with negative results. The oil in this horizon, although no accurate data are obtainable, is of lighter color and higher gravity than the normal Homer crude, and may represent lighter fractions brought up with the escaping gases.

Possibilities of Deeper Production

The possibilities of deeper production seem to be limited to the Comanche series, as several wells favorably located on the structure have penetrated all of the Gulf series with negative results.

Recent drilling in northern Louisiana has obtained both oil and gas from the Comanche series. In the Cotton Valley field two producing horizons, one in the anhydrite zone and the other in the upper part of the lower Glen Rose, are producing gas and oil. In the Pine Island field, several horizons in the lower Glen Rose yield oil and gas, as well as the upper beds in the red shale and sand zone.

The Homer dome is much more pronounced than the Cotton Valley dome, and reservoir conditions are equally, if not more, favorable to the accumulation of oil and gas. The faulting in the Homer field may have produced fracturing in the more competent strata, thus enhancing the reservoir conditions.

Although the structure of the Comanche series in the Homer field is not known, it has been determined that the major fault has displaced the red beds in the upper part of the Trinity group in the same manner in which the Gulf series are displaced. In locating a deep test, it is, therefore, important to consider the inclination of the fault plane, as the apex of the structure will move farther and farther toward the south as the depth of the beds increases. The dry territory that separates the north and south fields may reasonably be expected to be structurally high in the anhydrite zone and the lower Glen Rose, and a test well should be located with these facts in mind.

The Homer dome, considering the structure and the reservoir conditions, is perhaps the most promising area in which to test the oil- and gas-producing possibilities of the Comanche series.

Production

Drilling Methods

The rotary method of drilling was used in the Homer field, although a few wells were standardized after reaching the producing sand and completed with cable tools. The drilling presented no exceptional difficulties.

The common practice was to set 150–75 feet of 10-inch casing to exclude the surface waters. In the north field, where only the Nacatoch sand produced, 6-inch casing was set above the sand. In the south field, where both the Nacatoch and Oakes sand were productive, it was customary to leave a casing seat and rat-hole through the Nacatoch sand. If the show-

ing of oil warranted, a test casing was set; otherwise the hole was drilled to the Oakes sand and casing set above this sand. All casing strings were cemented.

The practice in completing the wells differed. In the north field, where bottom water was absent, most of the wells were drilled through the entire thickness of the Nacatoch sand and were allowed to flow through the casing. In most wells, however, $4\frac{1}{2}$-inch perforated liners were set through the sand. In the south field, the Nacatoch wells were commonly completed with $4\frac{1}{2}$-inch perforated liners, but sand screens were used in many of the wells. Depending upon the volume of fluid to be handled, 2-, $2\frac{1}{2}$-, or 3-inch tubing was used.

PRODUCING AREA

The total producing area of the Homer field is 2,280 acres, of which 1,250 acres are in the north field and 1,030 acres are in the south field.

In the north field, 295 wells were drilled, all to the Nacatoch sand, giving an average spacing of 4.3 acres per well. The depths of the wells range from 1,050 to 1,450 feet.

In the south field, 337 wells were drilled: 198 wells were completed in the Nacatoch sand, and 129 wells in the Oakes sand. The depths of the Nacatoch-sand wells range from 1,350 to 1,500 feet, and of the Oakes-sand wells, from 2,000 to 2,100 feet.

WATER CONDITIONS

The water conditions vary widely between the north and south fields. In the north field, producing solely from the Nacatoch sand, the edge water was closely delineated by the 1,100-foot contour. Bottom water was not present, and the encroachment of the edge water has been very slow. The present edge-water line conforms closely to the 1,025-foot contour. In the south field, the water conditions in the Nacatoch sand were similar to those in the north field, but, because of imperfect water shut-off, water appeared early. At the present time, all of the Nacatoch wells make water.

In the Oakes sand, bottom water was not far below the oil-producing sand. In the large wells which only tapped the oil sand, water ordinarily appeared in a few hours after the well began producing; and all of the wells, regardless of their initial production, made water shortly after completion.

INITIAL PRODUCTION

In the early stage of its development, the Homer field was featured by wells of high initial yield. Owing to inadequate pipe-line and storage

facilities, it was difficult to secure accurate gauges of the capacities of the larger wells; but competent production men estimated that one well had an initial yield of 40,000 barrels per day from the Oakes sand, and several

TABLE VI

PROPERTIES OF HOMER CRUDE OIL

ANALYSIS

Specific gravity	0.844	Baumé gravity	35.9
Saybolt universal viscosity:		Percentage of sulphur	0.63
At 70° F.	61.0	Percentage of water	Nil
At 100° F.	45.8	Pour test, below	5° F.

DISTILLATION, BUREAU OF MINES, HEMPEL METHOD

Temperature (Degrees C.)	Percentage of Cut	Sum Percentage	Specific Gravity Cut	Degrees Bé. Cut	Viscosity	Cloud Test (Degrees F.)	Temperature (Degrees F.)
Air Distillation. Barometer, 740 Mm. First Drop, 27° C. (81° F.)							
Up to 50							Up to 122
50–75	3.5	3.5	.670	79.0	......	......	122–67
75–100	4.1	7.6	.698	70.6	......	......	167–212
100–125	6.0	13.6	.725	63.1	......	......	212–57
125–50	5.5	19.1	.745	57.9	......	......	257–302
150–75	5.3	24.4	.764	53.2	......	......	302–47
175–200	5.8	30.2	.781	49.3	......	......	347–92
200–225	4.8	35.0	.796	45.9	......	......	392–437
225–50	5.5	40.5	.812	42.4	......	......	437–82
250–75	5.2	45.7	.826	39.5	......	......	482–527
Vacuum Distillation. Barometer, 40 Mm.							
Up to 200	5.0	5.0	.851	34.5	41	18	Up to 392
200–225	5.5	10.5	.857	33.4	47	28	392–437
225–50	5.9	16.4	.871	30.7	61	46	437–82
250–75	5.1	21.5	.880	29.1	87	64	482–527
275–300	5.9	27.4	.892	27.0	149	84	527–72

Carbon residue of residuum, 8.2 per cent.

APPROXIMATE SUMMARY

	Percentage	Specific Gravity	Degrees Bé.
Gasoline and naphtha	30.2	.736	60.2
Kerosene	15.5	.812	42.4
Gas Oil	10.5	.854	33.9
Light lubricating distillate	11.0	.875	30.0
Medium lubricating distillate	5.9	.892	27.0

wells producing from the same sand were rated as ranging from 10,000 to 25,000 barrels per day. The Nacatoch wells were smaller, but several were estimated to be capable of producing at the rate of 4,000–12,000 barrels per day.

A rather exceptional condition exists in this field in that no wells were completed as gas wells.

The character of the oil is shown by the analysis given on p. 225 by the United States Bureau of Mines.

PRODUCTION STATISTICS

The Homer field up to January 1, 1928,[1] has produced 56,053,456 barrels, distributed as shown in Table VII. The daily production to January 1, 1928, was 4,360 barrels from 482 wells, giving an average daily yield of 9 barrels per well.

TABLE VII

YEARLY PRODUCTION, HOMER FIELD

Year	Barrels
1919	1,994,165
1920	22,182,836
1921	12,736,884
1922	6,293,809
1923	3,801,938
1924	2,891,580
1925	2,345,000
1926	2,105,255
1927	1,751,989
Total	56,053,456

The Homer field has yielded the most oil per acre of any field in northern Louisiana. On a basis of the actual producing area of 2,280 acres, the average production per acre to January 1, 1928, is 24,500 barrels, as compared with 10,360 barrels per acre for the Bellevue field and 7,366 barrels per acre for the Haynesville field. Individual leases in the field have yielded in excess of 50,000 barrels per acre.

PRODUCTION DECLINE AND FUTURE PRODUCTION

In Figure 11 is given an average daily production decline curve for the Homer field, upon which has been projected an estimate of the future production to the end of the year 1935.

[1] Since this paper was written, the 1928 production figures are available: 1,662,779 barrels.

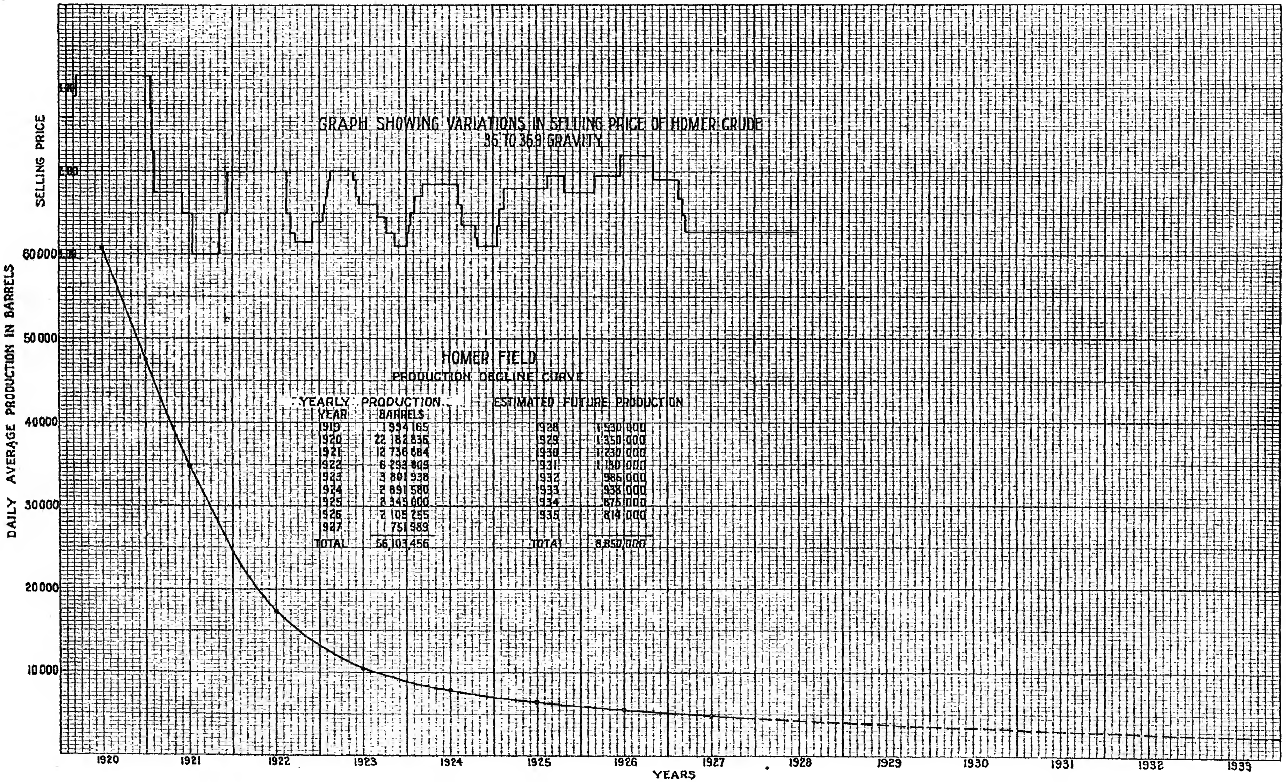


FIG. 11.—Average daily production decline curve of the Homer field. Shows estimated future production and price ranges of Homer crude oil.

The estimated future production by years is given in Table VIII.

TABLE VIII

ESTIMATED FUTURE PRODUCTION OF THE HOMER FIELD

Year	Barrels
1928	1,530,000
1929	1,350,000
1930	1,230,000
1931	1,130,000
1932	985,000
1933	938,000
1934	875,000
1935	814,000
Total estimated future production	8,850,000

SUMMARY OF PRODUCTION

The total production to January 1, 1928, was 56,053,456 barrels, the estimated future production 8,850,000 barrels, giving a total ultimate production of 64,903,456 barrels. The average acre yield based on these figures is 28,500 barrels per acre.

BELLEVUE OIL FIELD, BOSSIER PARISH, LOUISIANA[1]

L. P. TEAS[2]
Houston, Texas

ABSTRACT

The Bellevue oil field, in northwestern Louisiana, has produced in five years 8,500,000 barrels of 19.3° Bé. gravity oil from the Nacatoch sand, of Upper Cretaceous age, at a depth ranging from 300 to 400 feet. The field lies at the apex of a broad dome having a closure of about 800 feet. The accumulation of the oil is directly associated with a series of tensional faults. The faults in the Upper Cretaceous range in throw from 20 to 250 feet, but in the Lower Cretaceous a central horst has been faulted up 800 feet. Recently a deep well on this dome has penetrated much older beds than any hitherto encountered in Louisiana.

ACKNOWLEDGMENT

The writer is indebted to W. C. Spooner for kindly interest and helpful discussion of this paper and to Miss A. C. Ellisor and F. W. Rolshausen, of the Humble Oil and Refining Company laboratories, for helpful discussion and many paleontological data.

LOCATION

The Bellevue oil field is in Secs. 10, 11, 14, 15, and 23, T. 19 N., R. 11 W., eastern Bossier Parish, in northern Louisiana. It is 22 miles, by good road, northeast of Shreveport, and 5 miles north of Princeton, a station on the Shreveport branch of the Louisiana and Arkansas Railroad. The name is from the town of Bellevue, a few miles northwest of the field, the former parish seat of Bossier Parish.

HISTORY

Although Bellevue did not become a commercial producer of oil until R. O. Roy, on November 13, 1921, brought in his Railroad Lands No. 7, mention was made of the peculiar topographic conformation of the area as early as 1888 by L. C. Johnson,[3] who referred to "the hilly-like mass of

[1] Presented before the Association at the Tulsa meeting, March 25, 1927. Manuscript received by the editor, June 7, 1928.

[2] Geologist, Humble Oil and Refining Company.

[3] L. C. Johnson, "Report on the Iron Regions of North Louisiana and East Texas," *Ex. Doc. 195, 50th Congress.*

older Tertiary material entirely surrounded by level upland flats" which is the topographic expression of the dome. Veatch[1] shows this Tertiary inlier on his map accompanying the paper on the "Underground Waters of North Louisiana and South Arkansas," and G. D. Harris[2] shows it on his map of North Louisiana and South Arkansas.

Evidently the fact that a great dome existed here was not fully realized by these men, and it was not until 1917 that the Standard Oil Company of Louisiana, acting on the advice of its geologist, S. C. Stathers, drilled the Heilperin well, in Sec. 32, T. 20 N., R. 11 W. This well was on the north flank of the dome, and, although very much higher than it should have been normally, it was still too far down the flank to get commercial production. Showings were encountered, however, in the Nacatoch at 1,059 feet and again in the Woodbine at 2,414 and 2,521 feet.

J. Y. Snyder and R. O. Roy were next attracted to the area, and in 1919 drilled the Pease well located by Snyder in Sec. 26, T. 19 N., R. 12 W., which showed oil in the Nacatoch at 920 feet. In 1920 Roy's third well, Smith No. 1, Sec. 7, T. 19 N., R. 11 W., was completed as a 12-barrel pumper in the Woodbine at 2,173 feet. This oil was of excellent quality with a gravity of 38.2°. Three additional wells were drilled, all showing oil in the Nacatoch sand, until the Nacatoch was found so near the surface that a smaller rig could be used. Meanwhile The Texas Company drilled the Scanland No. 1 in Sec. 29, T. 19 N., R. 11 W., to 4,052 feet, encountering the Glen Rose anhydrite at about 2,770 feet. With the geological aid of Snyder, Roy continued his prospecting with a small rig during 1921 until November 13, 1921, when the tenth well (or the sixteenth, if the deeper tests are included) found commercial oil in the Nacatoch sand, near the top of the Upper Cretaceous. The discovery well, Railroad Lands No. 7, Sec. 15, T. 19 N., R. 11 W., encountered oil at 398 feet, or 184 feet below sea-level. This well opened what is perhaps the most productive field for its depth in this country. From then on, the development of the field by the Louisiana Oil Refining Corporation, the Standard Oil Company of Louisiana, the Gulf Refining Company, the Humble Oil and Refining Company, George Wetherbee, R. L. Autrey, and others was rapid, and an area of 700 acres was soon producing in the north pool. Later, in Secs. 22 and 23, T. 19 N., R. 11 W., $1\frac{3}{4}$ miles south of the discovery well, a small pool of about 100 acres was opened, but the wells were much below the standard of the main pool.

[1] A. C. Veatch, *U. S. Geol. Survey Prof. Paper 46* (1906).

[2] G. D. Harris, *U. S. Geol. Survey Bull. 429* (1909).

In 1923, Holman and Campbell[1] described the field as it had been developed to that time; since then, however, drilling has added enough additional information to justify another paper.

TOPOGRAPHY

The structural dome at Bellevue is well expressed on the surface. The Midway clay on the central part of the dome has weathered more rapidly than the surrounding Wilcox and Claiborne sands, thus producing a broad flat basin, open on the east side, with an average elevation of 215 feet. Within the basin the ground is ordinarily wet and the area is dotted with many small circular mounds, or "gas bumps," probably produced by rising ground water. With the exception of a few small prairies on the east side, the area was formerly heavily timbered. Around the central basin, within which the oil field lies, is a ring of rolling terrain and hills, which on the north and southwest sides exceed 400 feet in height. Brushy Creek flows south through the center of the field, but does not afford very effective drainage, owing to the flat surface within the basin area.

GEOLOGY

The geology of Bellevue is of exceptional interest, for here not only has the Nacatoch sand been brought closer to the surface than at any other point in Louisiana with the exception of the salt domes but the doming has been attended with much tensional faulting and by recurrences of the uplifting movement which have produced a marked unconformity (Fig. 1). In addition, on the surface the underlying structural conditions have been reflected in the stratigraphy and in the topography.

The Bellevue dome covers an area approximately 8 miles in diameter. Although not strictly a part of the Sabine uplift, it lies on the eastern flank of that adjoining and more extensive structure. Although both uplifts may have occurred at approximately the same time, they are of distinctly separate origin, the Sabine uplift having been caused by a broad folding movement, whereas Bellevue is probably the result of localized movement, probably igneous, rather than salt-dome activity.

The expression of the dome at the surface may be seen on the west side, from Fillmore north to Princeton, where successively older Wilcox and Claiborne beds are encountered until at Princeton the younger Claiborne (Cane River) again appears in a down-faulted block. Farther northward, near the village of Bellevue, the Wilcox again crops out and is overlain by Cane River clays and still younger Sparta sand. The exposure

[1] E. Holman and R. B. Campbell, *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), p. 645.

of older formations near the center of the dome is prevented by a Pleistocene deposit of sand and clay. This central deposit was made possible by

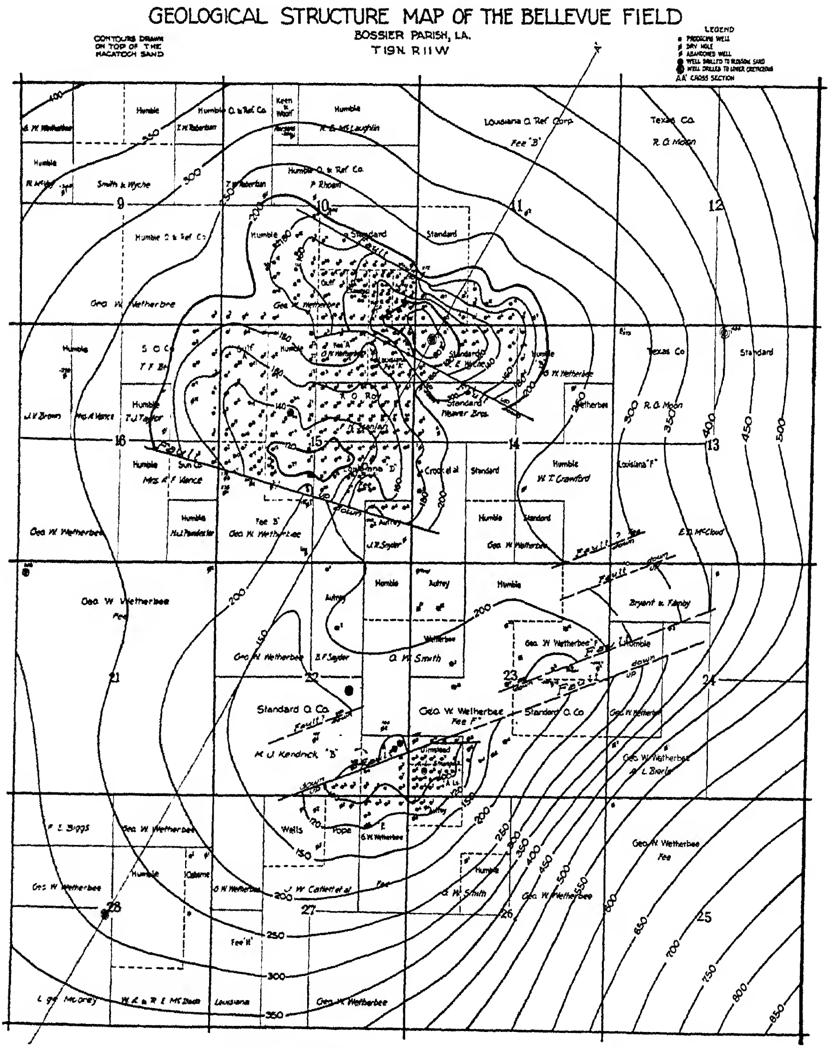


FIG. 1.—Subsurface structure of Bellevue dome, contoured on top of Nacatoch sand below sea-level. Contour interval, 50 feet.

the previous erosion of the more easily eroded Midway clay, while the flanking Wilcox and Claiborne sands, less easily eroded, were left.

STRATIGRAPHY

Owing to the continuation of uplift during deposition, to faulting followed by erosion, and to the erosion of the domed area, the normal north Louisiana section is not found everywhere at Bellevue. Some of the Tertiary and Upper Cretaceous formations have thinned over the top of the dome; the lower part of the Upper Cretaceous is missing at the apex; and approximately 1,150 feet of the upper Trinity are also missing over the center of the dome. On the other hand, the limes and shales are somewhat thicker near the middle of the Trinity section (Fig. 2).

The Wilcox is the oldest formation at the surface, although the Midway on the top of the dome lies below approximately 80 feet of Pleistocene fluvio-estuarine deposits. The next youngest formation exposed is the Sparta sand of middle Claiborne age, and some miles distant still younger Claiborne occurs.

Beneath the surface, on top of the dome, the Lower Cretaceous has been penetrated to a depth of more than 4,200 feet below the top of the Trinity, or to a greater depth than elsewhere in Louisiana.

LOWER CRETACEOUS SERIES

Glen Rose formation.—The Glen Rose formation on the flanks of the Bellevue dome is represented by the normal northern Louisiana section, thickened a little from Caddo and Cotton Valley, owing to its position farther from the shores of the Glen Rose embayment. Wells drilled on top of the dome, however, found the section much reduced by faulting, later erosion, and possibly even by interrupted deposition. The term "Glen Rose" as here used is restricted to the upper calcareous beds of Trinity age, which, from their fossils, may be correlated with the Glen Rose of Texas. The middle series of red shales and sands and the lower calcareous measures encountered in the Humble Oil and Refining Company's Bliss and Wetherbee No. 30 are given only descriptive terms until their exact correlation has been definitely established.

The Glen Rose of Louisiana may be divided into three parts: an upper lime and clay series with a few red beds totaling normally 600 feet or more but thinning to nothing on top of the Bellevue dome; a central anhydrite series, broken with beds of limestone and dark gray shale, about 500 feet thick; and a lower lime and shale section ranging from 1,000 to more than 1,100 feet in thickness, and containing two pisolitic zones: one comprising the upper 300 feet of the section and the other in the lower 200 feet. The Glen Rose, as here defined, is correlated by Miss A. C. Ellisor with both the DeQueen and Dierks limestones and

TABLE I

GEOLOGICAL FORMATIONS AT BELLEVUE

Series	Group and Formation		Thickness in Feet	Lithology
Recent			3	Gray sand, silty sand, and clay
Pleistocene	Citronelle		80	Red clay and sand with white lime nodules
Eocene	Claiborne group	Sparta sand	400+?	Gray sand with chocolate clay and lignite. Some ferruginous sandstone
		Cane River clay	100	Glauconitic sand and clay with ferruginous concretions containing some fossil casts. Weathers deep red
	Wilcox formation		500	Cross-bedded gray sand; sandy clay; chocolate clay, and lignite. Boulders of calcareous sandstone
	Midway clay		590	Blue to black clay with siderite concretions. Clay is brittle near base, and basal 35 feet is calcareous
Upper Cretaceous	Arkadelphia clay		40	Gray calcareous clay and lime. Very fossiliferous
	Nacatoch sand		325	Calcareous sandstone and limestone, streaks of shale. Basal part consists of calcareous shale
	Saratoga chalk		333	White fossiliferous chalk
	Marlbrook clay			Gray calcareous marl and chalk
	Annona chalk			White, poorly fossiliferous chalk
	Ozan formation		200	Gray to blue calcareous slightly sandy clay
	Buckrange sand		75	Glauconitic sand equivalent to the so-called "Blossom"
	Brownstown clay		200	Gray and blue calcareous fossiliferous clay
	Tokio formation		400	Clay, sand, and volcanic ash
	Eagle Ford clay			Red and gray clay; soft and hard lime. Missing in part on top of the dome
	Woodbine sand			Coarse mealy sand with white kaolinitic cement. Some red and gray clay. Missing on top of dome

Depth, 5,260–61 feet. *Foraminifera*, mostly pyritized; some distorted but generically recognizable.

Polymorphina (Guttulina) sp. Well preserved. This genus occurs from Jurassic to Recent. It does not occur in the Paleozoic. 5 specimens.

Holophragmium aff. *aequolis* (Roemer). 10 specimens. Cretaceous, not in the Paleozoic.

Hoplaphragmoides sp. 10 specimens. Arenaceous with little calcareous cement. Like Mesozoic, but not like Paleozoic forms.

Gastropoda and *Ostracoda*. This fauna is definitely Mesozoic and can not be Paleozoic. It is either Lower Cretaceous or Jurassic—more probably Lower Cretaceous.

This determination seems to be in accord with the structural evidence as the last 330 feet does not seem faulted or disturbed differently from the beds above that have been definitely called Cretaceous; and the limy shales of Cretaceous age at 4,882 feet have evidently graded into these lower beds and are of somewhat the same lithologic character.

The faulted Glen Rose section and the succeeding 2,391 feet of Trinity or older beds in the Bliss and Wetherbee No. 30 were thoroughly cored, so that a rather complete section (Table II) is appended, from the reports of Miss A. C. Ellisor and F. W. Rolshausen.

In the section shown in Table II the Glen Rose division of the Trinity group was represented from 1,853 feet, where the first *Miliolidae* were found, to 2,909 feet, where a red shale and sandstone series began, of non-marine, or at least brackish-water, origin and not included in the present paper within the Glen Rose. These lower Trinity red beds have a total thickness of 992 feet in the Bellevue section and are succeeded by 1,072 feet of red and white sands, still less marine in their character, which have been temporarily designated in this paper as the Trinity sands. Finally, the last 330 feet of the Bliss and Wetherbee well is decidedly marine. The fauna in this series suggests strongly that it is of Lower Cretaceous age although it does not occur in any of the Trinity formations known elsewhere in Louisiana. It is probable that these beds are the older and more basinward deposits of the Lower Cretaceous sea and may be related to the pre-Trinity beds of northeastern Mexico.

UPPER CRETACEOUS SERIES

Woodbine formation.[1]—The Woodbine is not encountered on top of the dome but begins from 1 to 2 miles out and gradually thickens in all directions until in the Carterville area, 22 miles north of Bellevue, it is a pro-

[1] The Woodbine sand as noted in wells in northern Louisiana (Triangle Drilling Company's Keen No. 1, Sec. 7, T. 19 N., R. 5 W., Claiborne Parish; Arcadia Syndicate's

TABLE II

RÉSUMÉ OF LOG OF HUMBLE OIL AND REFINING COMPANY'S BLISS AND WETHERBEE NO. 30

LOWER CRETACEOUS SECTION

Principal Characteristics of Beds	Depth in Feet	Thickness in Feet
Anhydrite	Missing	500
Oölitic lime and gray shale	Missing	50–100
White *Miliolidae* limestone and gray to green clay	1,853–1,978	125
Black lime concretions	1,958–78	20
Brownish-gray pisolitic and oölitic limestone *Miliolidae* and *Ostracoda*	1,978–94	16
Gray limestone *Miliolidae* and *Ostracoda*	1,994–2,071	77
Oölitic and pisolitic dark gray crystalline limestone, also tan-colored limestone; sandy lime with lignitic shreds and shale and sandstone lenses *Ostracoda*	2,071–2,208	37
Shell breccia with medium gray lime matrix *Serpula*	2,208–32	24
Tan and gray crystalline limestone *Serpula*	2,232–40	8
Medium-textured calcareous sandstone	2,240–86	46
Light gray and crystalline limestone *Serpula*	2,286–2,317	31
Gray to greenish calcareous clay and soft gray lime *Serpula*	2,317–67	50
Gray to greenish-gray hard lime with streaks of gray and greenish calcareous clay *Ostracoda*, *Foraminifera*, and *Serpula*	2,367–2,659	292
Dull brown shaly calcareous clay with some fine-textured sandstone; gray and brownish-gray crystalline limestone and soft gray lime *Ostracoda*, *Serpula* to 2,713 feet, and large fossils, but no *Foraminifera*	2,659–2,858	202
Gray, pisolitic limestone *Ostracoda* (Dierks)	2,858–64	6
Gray limestone and gray and brown calcareous clay *Ostracoda* (Dierks)	2,864–2,911	47

TABLE II—*Continued*

Principal Characteristics of Beds	Depth in Feet	Thickness in Feet
Greenish-gray to brown non-calcareous fine-textured sandstone with siderite cement; light chocolate-colored micaceous shale; and dull brick-red shale (bentonitic clay from 2,921 to 2,961 and from 3,373 to 3,490) Fossils consist of *Ostracoda*, *Chara* seeds and a few shells down to 3,089 only	2,911–3,900	990
White, fine- to medium-grained, non-calcareous sandstone for the most part, with a few thin layers of dark brown calcareous sandy clay; some non-calcareous sandy clay and dark red clay and sandstone in subordinate amounts	3,900–4,972	1,072
Dark gray, brittle, slightly calcareous shale; hard fossiliferous clayey and sandy lime (*Foraminifera* and *Ostracoda* which have been identified as either Lower Cretaceous or possibly Jurassic in age)	4,972–5,302 Total depth	330

ducing horizon. However, it again thins and disappears on the Sabine uplift at the west. It consists of a coarse-grained sand with numerous fragments and pebbles of volcanic rock and tuff, cemented with white arkosic clay. Beds of non-calcareous gray and red clay and lenses of fine-grained gray sand occur through the formation.

Eagle Ford clay.—The Eagle Ford clay here is medium gray calcareous shale with streaks of micaceous sandy shale; dark gray non-calcareous shale; and some red shale. In the Bliss and Wetherbee No. 30, on top of the dome, only beds of definite upper Eagle Ford clay have been recognized by Miss Ellisor. Although no large Eagle Ford fossils have been found in this well, these clays contain the typical *Foraminifera* found in the upper part of the Eagle Ford in Texas.

McGuire No. 1, Sec. 30, T. 18 N., R. 5 W., Bienville Parish; and others) has been recognized by Miss A. C. Ellisor to be lithologically similar to the Woodbine sand found in wells in eastern Texas. The basis for this correlation is a green sand near the center of the formation, composed largely of glauconite of distinctive color and texture and lying below shales containing Eagle Ford fossils. In addition the Louisiana Woodbine has been identified as having the same distinct mineral and textural characteristics of the sand occurring along the outcrop zone in southwestern Arkansas recognized by Dane ("Oil-Bearing Formations of Southwestern Arkansas," *U. S. Geol. Survey Press Notice 8823* [1926]) as Woodbine and correlated with the Woodbine of northern Texas. This distinctive lithology has not been noticed in the Lower Cretaceous. The true Woodbine sand therefore is known to occur on the west, north, and east sides of the Sabine uplift, evidently feathering out in the direction of the uplift, possibly because that area was exposed to erosion during Woodbine time.

Tokio formation.—The Tokio consists of dark gray slightly sandy and micaceous calcareous shale. Fine-grained glauconite also occurs. Fossils are relatively few.

Brownstown clay.—The Brownstown formation is dark gray calcareous shale with streaks of fine- to medium-grained sand with a little glauconite. It contains a prolific micro-fauna.

Buckrange sand.—The Buckrange is a greenish-gray to green, medium- to fine-textured sand and calcareous clay with fine-grained glauconite and some coarse, flinty grains and pebbles. The sand is fossiliferous.

TABLE III

TYPICAL NACATOCH SAND RECORD

STANDARD OIL COMPANY'S WYCHE NO. 3,
SEC. 14, T. 19 N., R. 11 W.

Description of Formation	Depth in Feet
Sandy streaks of lime	330–33
Soft sand	333–38
Sand and rock showing oil	338–40
Sand and streaks of lime	340–66
Sand	366–69
White sand	369–80
Gumbo	380–85
Sand	385–92
Sand rock	392–98
Sand	398–400

Ozan formation.—The Ozan formation consists of dark gray micaceous calcareous clay and sandy clay. It contains chalky streaks near the top and some hard sandy boulders with a fauna quite distinct from the Brownstown clay below.

Annona chalk.—The Annona is light gray to white massive chalk with a sparse fauna. It is irregular in thickness, and locally it becomes more clayey or more chalky.

Marlbrook marl.—The Marlbrook is dark gray, highly fossiliferous marl.

Saratoga chalk.—The Saratoga chalk, although poorly developed here, is light gray sandy marl or impure chalk containing fossils.

Nacatoch sand.—The Nacatoch sand is the producing formation at Bellevue. It is a calcareous, medium-grained sand and sandstone series varying within short distances from pure sand to very sandy lime. In places the lime is very porous, thus accounting for the irregularity of the

production in different wells. Ordinarily several hard streaks or caps are encountered, and breaks of shale or gumbo occur in the lower part.

Arkadelphia clay.—The Arkadelphia is a calcareous clay or gumbo ranging to a soft white fossiliferous lime, lying immediately above the Nacatoch sand. Its thickness on the dome is approximately only 40 feet, showing a considerable thinning from the 200 feet encountered in southern Arkansas.

EOCENE SERIES

Midway formation.—The Midway is not exposed at Bellevue, owing to a later covering of Quaternary and Recent sand and clay. In the wells on or near the dome, its thickness ranges from 240 to 590 feet. It is dark blue non-calcareous clay with siderite boulders and about 30 feet of gray fossiliferous calcareous clay at the base. The calcareous Midway, except that it is slightly more gritty, is hardly distinguishable lithologically from certain phases of the Arkadelphia. At the base of the Midway some sand and a few phosphate nodules occur.

Wilcox formation.—The Wilcox formation in this area consists of gray and chocolate clay and highly cross-bedded sand and sandy clay with beds of lignite ranging from a few inches to 6 feet in thickness. Typical gray, sandy calcareous boulders occur in the Wilcox, particularly along Bodcaw Bayou. The contact between the Wilcox and the Claiborne may be seen in the Fillmore-Princeton road 0.7 mile south of Princeton. A section of the cross-bedded Wilcox sand from the base of the Cane River is well exposed on the road leading down to the Bodcaw Bayou bridge 1½ miles northwest of Bellevue. A boulder horizon occurs along the east side of the bayou above the bridge about 50 feet below the top of the Wilcox. The boulders extend down the bayou for 5 miles below the bridge.

Cane River clay.—The Cane River clay, the basal Claiborne member, is well exposed along the Shreveport-Minden road from Red Point, 2 miles west of Fillmore, to Brushy Creek, a mile east of Fillmore. The Cane River here is a glauconitic sandy clay with few large fossils and no *Foraminifera.* From Fillmore northward for a mile along the Bellevue road the Cane River consists of dark clay with beds of limonitic concretions having small fossil casts. Exposures of the base of the Cane River, where a dark glauconitic boulder zone is found, may be seen in the Louisiana and Arkansas Railroad cut 0.3 mile west of the Fillmore-Bellevue road; at Bellevue; and a mile northwest of Bellevue on the road leading to Bodcaw Bayou.

In the north half of the NE. ¼, Sec. 2, T. 20 N., R. 11 W., on the west

side of the Jenkins farm, in a gully behind the house, fossiliferous, gray-green, somewhat glauconitic upper Cane River clay occurs just below the Sparta sand. *Venericardia*, *Ostrea*, and other common Eocene genera occur here, but no *Foraminifera* have been observed.

Sparta sand.—In the vicinity of the Bellevue field the Sparta sand is well exposed at two localities. The best exposure is in a hill on the Jenkins farm in the NW. ¼, NE. ¼, Sec. 28, T. 20 N., R. 11 W., where approximately 60 feet of heavy, gray sand with dark brown sandstone fragments is in contact with the upper, gray-green, fossiliferous clay of the Cane River. On a high hill about a mile southwest of Fillmore in Sec. 14, T. 18 N., R. 11 W., the Sparta sand is 60 feet in thickness. Some brown sandstone and limonitic concretionary beds also occur through this sand.

PLEISTOCENE SERIES

Beds of Pleistocene age, sometimes referred to as the Port Hudson, attain a thickness of about 60 feet on the Bellevue dome. These beds consist of fluvio-estuarine deposits generally occurring on terraces or forming the bottoms along the rivers and larger creeks of the present drainage. At Bellevue, Midway clay on the dome had already been eroded, probably during the Pliocene, so that a basin existed whose level was about the same as that of the Pleistocene estuaries. Borings made near the northwest corner of Sec. 14, T. 19 N., R. 11 W., show the series to consist of red clay with thin red and gray sand lenses and irregularly shaped lime nodules.

RECENT

A veneer of gray silty clay and sand ranging in thickness from 1 foot to 3 feet was recently deposited over most of the Bellevue area, concealing the red Pleistocene formation.

STRUCTURE

Bellevue consists of a broad dome having a closure of 830 feet on top of the Nacatoch sand, which is found at the apex of the dome as shallow as 280 feet below the surface. Eastward from the top of the dome there is a long slope for 9 miles, until the Nacatoch is found deeper than 2,100 feet in Sec. 31, T. 20 N., R. 9 W. Toward the north a slope of 12 miles places the depth of the Nacatoch at 1,800 feet in Sec. 4, T. 19 N., R. 11 W., and toward the south, in Sec. 11, T. 18 N., R. 11 W., at a distance of 5½ miles from the top of the dome, the Nacatoch is 1,300 feet deep. On the west side a saddle connects the dome with the Sabine uplift, so that the smallest closure is found there. The broad, gently sloping character of

the dome, so clearly shown, when drawn to scale, as is the accompanying cross section, suggests that intrusive salt cannot explain its origin.

The main oil pool covers about 700 acres on the top of the dome, and three other oil and gas pools of much smaller extent lie farther down the flanks. The productive closure of the main pool is 120 feet, but there is much less closure on the smaller pools.

Several faults cut the Nacatoch sand and the Upper Cretaceous series. The main pool is limited on the north by a 20-foot fault extending southeast and northwest; and on the center of the east side of this pool two small faults having a throw ranging from 50 to 75 feet extend southwest. Another fault with a maximum throw of 110 feet limits the main pool on the south. This fault also extends generally southwestward.

The south pool, which covers only about 100 acres at the intersection of Secs. 22, 23, 26, and 27, T. 19 N., R. 11 W., is limited on the north by a northeast-southwest fault having a throw of 100 feet. It is this fault whose southwest end is expressed on the surface by the downthrown block of Cane River along the road near Princeton. Two other faults north of this fault form a graben area. The east end of this graben is very narrow and is therefore mapped as a unit separate from the much wider graben at the west end. The throw at the east end is also much greater, for it evidently exceeds 250 feet.

It is believed that a small graben exists near the northeast corner of Section 23. Other faults affecting the Upper Cretaceous will probably be revealed by further development. The arrangement of these faults on the dome and their character suggests that they have probably been produced by tensional stresses caused by doming of the Upper Cretaceous strata, and were therefore formed coincident with the doming.

The faulting in the Lower Cretaceous is of a different character and quite distinct from that in the Upper Cretaceous. It was probably caused by impact of possibly deep-seated igneous material which produced a wedge-shaped block or horst much as wedge-shaped fragments of glass are produced when a glass plate is struck by a blow from a hammer, the wedges originating at the point of impact.

One boundary of this horst possibly extends northwest and southeast near the northeast corner of Section 28, and another boundary may have passed through Section 11. This block was pushed up about 800 feet with respect to the low sides and base-leveled; probably the erosion was coincident with the uplift. Because of this uplift, the Standard Oil Company's Kendricks No. B-1, Humble Oil and Refining Company's Bliss and Weatherbee No. 30, and the Standard Oil Company's Wyche No. 2 pass

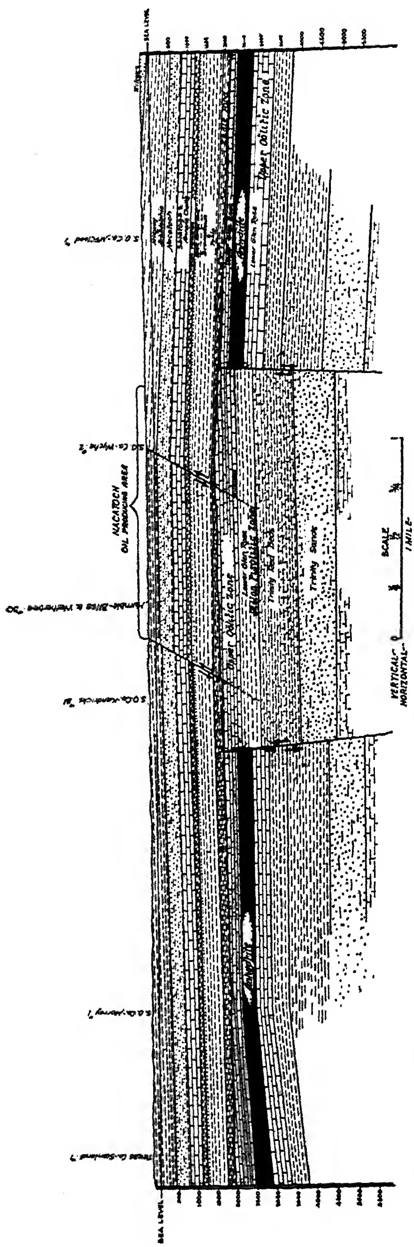


FIG. 3.—Generalized geologic section *A-A'* through Bellevue dome (Fig. 1). The two lower faults are hypothetical.—S. P.

from Upper Cretaceous Eagle Ford beds into the Trinity at a point about 1,200 feet below the top of the complete Glen Rose section. This relation may be seen in Figure 3. The two wells on the west side of the horst, Standard Oil Company's Moorey No. 1 in Sec. 28, T. 19 N., R. 11 W., and The Texas Company's Scanland No. 1 in Sec. 29, T. 19 N., R. 11 W., both encountered the upper measures of the Glen Rose, including the anhydrite and from 200 to 600 feet of Trinity beds overlying the anhydrite. On the east side of Bellevue the Standard Oil Company's McLeod No. 1 in Sec. 13, T. 19 N., R. 11 W., seems to be on the low side of the horst, since the lower Glen Rose was not encountered at 2,219 feet, its total depth. Fossils from 2,199 to 2,201 feet identified by Miss Ellisor as Eagle Ford occur 1,613 feet below the top of the Nacatoch, whereas in Bliss and Wetherbee No. 30 the maximum interval between the Nacatoch and the Eagle Ford is 1,508 feet. The log of the McLeod well shows oölitic limestone at 2,197 feet and 2,206 feet; but in the cores from 2,197 to 2,201 feet,

examined by Miss Ellisor, no oölites were found, although lime concretions were noticed.

RELATION BETWEEN PRODUCTION AND STRUCTURE

At Bellevue, production rather strikingly conforms to structure. In the main, or north pool, the original water level was about 190 feet below sea. When a well reached this point, either on account of the dip of the dome or by faulting, it was a failure. In the lower pool the water level ranged from 100 to 140 feet below sea, due probably to the irregular porosity of the producing zone. The Nacatoch sand at Bellevue is very limy in many places and in some wells the porous character of the lime rather than the sand was responsible for the large production. The large production of such wells as the Humble Oil and Refining Company's Bliss and Wetherbee No. 2, and the Gulf Refining Company's Bliss and Wetherbee No. 8, which made initially from 8,000 to 10,000 barrels of fluid, more than half of which was oil, was due to locally porous lenses of lime within the more sandy section. About eight gas wells have been drilled in the area between the two pools. These gas wells have different sub-sea depths, some of them approximately 200 feet, so that we must explain them by local accumulations in porous lenses sealed off from the main producing body.

A glance at the structural map shows the striking effect of faulting on the producing areas at Bellevue. Both pools are sharply cut off by faults, and the general appearance suggests that the oil has come up through the faults from a deep source and spread out into the Nacatoch sand, forming our present commercial pools. Although the boundaries of the Lower Cretaceous horst are not exactly known, because only a few wells have been drilled on or near it, the Nacatoch production seems to be restricted to the area lying above the horst. For this reason and because of the fact that much lower beds could be penetrated at this location, a site on the horst was selected for the joint test of the structure. Although the complete Trinity section was not drilled through in this well, only showings and saturated cores were found below the Nacatoch, so that whatever oil may have originally occupied the lower beds on the horst evidently passed upward into the Nacatoch or into some of the lower beds on the low sides of the block.

It is felt that the chances for production in the more complete Trinity section to be encountered on the sides of the horst are exceptionally good at Bellevue, since closures must exist in the flanking beds on all sides of

the horst, although the productive area may consist of narrow strips lying along the Lower Cretaceous faults.

GEOLOGIC HISTORY

Bellevue was evidently a structurally high area in fairly remote geologic time. After the deposition of a Lower Cretaceous section that was slightly thicker than that deposited a few miles north at Cotton Valley or at Pine Island, probably because of the deepening of the basin southward, uplift began in the Bellevue area and caused the complete removal of the Fredericksburg beds and erosion of at least 400 feet of upper Glen Rose on the top and upper flanks of the dome, since this is the difference in the thickness of the upper Glen Rose section in the Standard Oil Company's Moorey No. 1, near the top of the dome in Sec. 28, T. 19 N., R. 11 W., and The Texas Company's Scanland No. 1, in Sec. 29, T. 19 N., R. 11 W., farther down the side of the dome. Then a narrow block was thrust up, probably by deep-seated igneous activity, 800 feet relative to the flanking and already domed strata. The evidence indicates that this uplift was caused by faulting rather than by doming, since the three wells that have directly penetrated this block—the Humble Oil and Refining Company's Bliss and Wetherbee No. 30, and the Standard Oil Company's Kendricks No. B-1 and Wyche No. 2—have evidently touched the Glen Rose at horizons within 200 feet of each other, a coincidence that could scarcely have happened if the uplift had been caused by doming. We cannot assign a more definite age to this faulting than that it was post-Lower Cretaceous and pre-Eagle Ford. Perhaps it was coincident with the igneous activity that produced the intrusions and plugs of south-central Arkansas; the uplift, dikes, and extrusive deposits of the Monroe-Richland area of northeast Louisiana; and the sharp doming at Pine Island in Caddo Parish and elsewhere in northern Louisiana, all of which are regarded by some as having occurred following the close of Lower Cretaceous deposition.

The gentle contour of the dome in cross section minimizes the possibility of uplift by salt, for the action of salt produces almost straight sides. The dome is distinct from the Sabine uplift, and its sharpness and uniformity strongly suggest an igneous origin. Since igneous plugs are numerous in southern Arkansas, it is natural to associate the origin of Bellevue with igneous activity; other explanations seem much more illogical.

During this time the uplift of the horst proceeded as a definite unit distinct from any doming movement that may have affected the area, and

at a faster rate than the doming, since the upper Glen Rose beds are so sharply cut off at the edge of the horst. Of course, uplift and erosion may have begun in Glen Rose time and gone on simultaneously here until early Upper Cretaceous time, while deposits of Fredericksburg age were being deposited out from the dome and while Washita deposits were being laid down still farther off along the Texas-Louisiana line. The area was not completely reduced to sea-level prior to the deposition of the Woodbine sand, since that formation is missing over the center of the dome, or else further uplift in Upper Cretaceous time caused its removal. The submergence that attended the beginning of Eagle Ford time evidently did not affect the dome early enough to permit lower Eagle Ford deposition; but finally, during the later part of that time, erosion, or settling back of the area into the Eagle Ford sea, permitted the deposition of late Eagle Ford shales.

The remaining formations of the Upper Cretaceous series were then deposited in a normal manner, although a certain amount of doming continued through the entire period and well into Tertiary time. The final doming movement with attendant faulting, that is largely responsible for the structure in the Nacatoch there to-day, occurred possibly during the Miocene, since we infer that the dome was structurally complete prior to the deposition of the Pleistocene sand and clay, for these deposits must have been laid down in the circular basin over the center of the dome made possible by the easier erosion of the Midway clay, which of course did not appear at the surface until after the uplift. The fact that the Arkadelphia, Midway, Wilcox, and Claiborne are possibly slightly thinner on the dome and on the flanks of the dome than they are farther off, indicates the progressive character of the uplifting movement.

During Pleistocene time Bellevue was a shallow arm of the broader estuarine sea, almost surrounded by land. Still later, during Recent time, shallow water again invaded the area, accounting for the veneer of gray sand. This gray sand is even now being raised into small domes or "pimples" by rising ground water, and is the only formation on which these domes, still unaffected by erosion, have been found.

DEEPER PRODUCTION POSSIBILITIES

The Buckrange sand ("Blossom") in Roy's Pease No. 3, Sec. 25, T. 19 N., R. 12 W., showed oil. In the south pool, the average daily production of three wells was 7½ barrels of oil from the Buckrange at 1,030 feet, and some gas was produced from this horizon by the Standard's Kendrick No. A-1. Cores from 1,120 to 1,257 feet in the Humble Oil and Refining

Company's Bliss and Wetherbee No. 30 were partially saturated with oil, but several Halliburton tests showed only a handful. In this well the sand was poor, but wells farther down the flanks show much better sand conditions.

The best showing encountered from the Woodbine was in Roy's Smith No. 1, Sec. 7, T. 19 N., R. 11 W., at 2,173 feet. This well pumped 12 barrels of 38.2° Bé. oil in one day. On the top of the dome the Woodbine is missing, for in Bliss and Wetherbee No. 30 the lower Glen Rose is encountered directly beneath beds of upper Eagle Ford age, according to determinations made by Miss Ellisor.

The Standard Oil Company's Moorey No. 1 in Sec. 28, T. 19 N., R. 11 W., had about 10,000,000 cubic feet of gas at 2,622 feet, or about 270 feet below the top of the Glen Rose anhydrite. This well is making a little green, light oil through the casing head. The Glen Rose beds below the anhydrite in the Bliss and Wetherbee No. 30, consisting mostly of pisolitic and oölitic lime and porous crystalline lime, were partially saturated with oil of varying degrees of gravity from a point about 200 feet below where the base of the anhydrite should be (1,978 feet) to 1,200 feet below the anhydrite (2,910 feet). The red bed and sand series in this well were rarely petroliferous. Horizons with light oil saturation were encountered at 1,600 feet below the base of the anhydrite, or at a depth of 3,540 feet. Numerous Halliburton and Johnston tests were made of these showings, but only small quantities of oil were recovered. If the lower 330 feet in the Bliss and Wetherbee No. 30 is Lower Cretaceous, as the fossils suggest, then the possibility of production from basal Cretaceous sands is still present, although the depth to these sands is evidently so great that only very large wells in them would be profitable under the present economic conditions.

The question of deep production at Bellevue is therefore still unanswered. The Bliss and Wetherbee No. 30, although finding no commercial oil in the "Blossom" or Trinity, has far from condemned the deep possibilities of the dome; rather it has improved the prospects, since it revealed more than 500 feet of shales and limes below the lower red-bed series which had not been generally expected from previous drilling in northern Louisiana. Very little drilling has been done on the flanks of the dome to test the "Blossom," Woodbine, and upper Glen Rose possibilities, which were found encouraging in several wells. The flanks afford the greatest possibilities, since these horizons are missing or have thinned on top of the dome.

Excellent possibilities for production exist in the porous Glen Rose

zones below the anhydrite in the closed areas lying against the horst on the downthrown sides. The three deep wells drilled on top of the horst also show enough variation in depth to the oölitic zones to indicate that closed structural conditions also exist on the horst, and that ultimately production may be obtained in some lower sands there, although flank Trinity production seems now more likely.

THE BELLEVUE OIL

The oil produced at Bellevue from the Nacatoch, which constitutes practically the entire commercial production, has a gravity of 19.3° Bé. and contains a large amount of lubricating oil and little gasoline.

The analysis (Table IV) of the crude from the discovery well, Roy's Railroad Lands No. 7, was made by the Humble Oil and Refining Company.

TABLE IV

ANALYSIS OF BELLEVUE CRUDE FROM NACATOCH SAND

Constituent	Percentage	Degrees Bé. Gravity
Gasoline	2.5	63.6
Naphtha	2.5	54.2
Kerosene	7.5	43.3
Gas oil	12.5	33.5
Spindle oil	30.0	27.2
Lubricating oil	38.0	21.3
Loss and coke	0.7	....

Three wells at Bellevue produced small quantities of a lighter oil from the Buckrange ("Blossom") sand, at a depth of about 1,030 feet, in Sections 22 and 23. R. O. Roy's Smith No. 1, Sec. 7, T. 19 N., R. 11 W., produced about 10 barrels daily of a still lighter oil (an analysis of which is shown in Table V) from the Woodbine sand at a depth of 2,173 feet.

TABLE V

ANALYSIS OF WOODBINE OIL FROM R. O. ROY'S SMITH NO. 1
Gravity of the Crude, 38.2° Bé. Color, Black

Constituent	Percentage	Degrees Bé. Gravity
Gasoline	34	59.2
Kerosene	22	44.1
Fuel oil	43	19.5

From around the plug in the Moorey well in Section 28, a light, green oil is reported to be oozing in small quantities. No analysis of this

oil is available, but it is likely that it may be associated with the gas-producing horizon, in the Glen Rose anhydrite, encountered in this well.

PRODUCTION

From the discovery, production in many of the wells at Bellevue was accompanied by large amounts of water and sediment. The largest wells ordinarily had 60 per cent or more water in their fluid content. The oil was also very foamy, so that the production appeared to be several times larger than it actually was. In some wells and on some leases, particularly

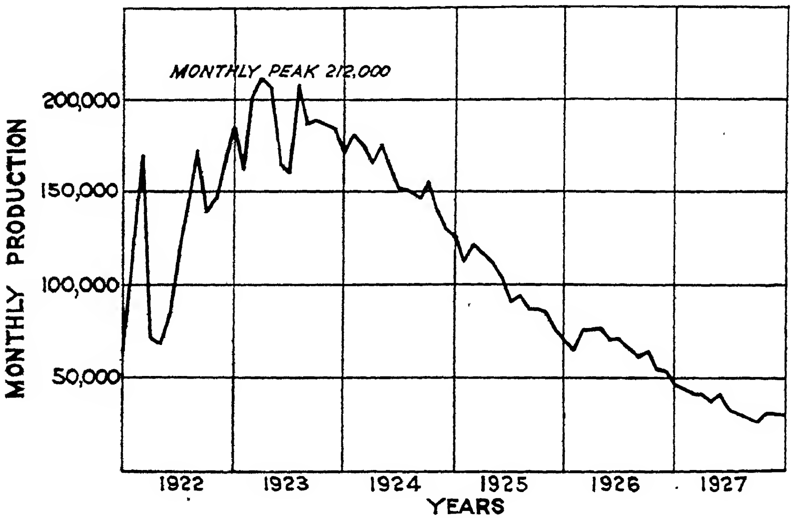


Fig. 4.—Production curve, Bellevue field.

R. L. Autrey's Elston lease and the Louisiana Oil Refining Corporation's Bodcaw Fee lease in Section 14, there was very little water at any time. Elsewhere, individual wells, surrounded by wells making large amounts of water, showed little or no water. This irregular condition was due to the irregular sand-and-lime content of the producing horizon; evidently small bodies of sand were sealed off from the rest of the reservoir by irregular cementation. After production had dropped off, it was found that by deepening some of the wells from 10 to 50 feet the net production could be increased, since lower porous oil-bearing lenses occurred irregularly distributed through the main body of sand.

During the last few years a rather extraordinary condition has been observed at Bellevue. The fluid has been decreasing: instead of raising 10,000 barrels of fluid to produce 300 or 400 barrels of oil, the wells have

dropped 50 or 75 per cent in fluid production, and some wells almost entirely, the oil content of course also decreasing. The periodic variation in the amount of fluid and in the oil content is also a peculiarity of the field (Fig. 4). The normal production of a lease would increase from 10 to 30 per cent for several days and then drop back to the old level or below it. Periodic increases in the water content of the production also occurred.

TABLE VI

WATER ANALYSES OF BELLEVUE WATER ZONES

Well	Depth in Feet	Formation	Chemical Constituents in Parts per Million	
			Chlorine	Sulphur Trioxide
Roy's Bliss and Wetherbee No. 3.	80	Pleistocene sand	38	
Humble Oil and Refining Co's Bliss and Wetherbee No. 13...	360	Nacatoch sand	15,000	Trace
Humble Oil and Refining Co's Bliss and Wetherbee No. 30*..	1,979–94	Glen Rose	30,600	1,875
	1,994		32,140	
Bliss and Wetherbee No. 30.....	2,091	Limestone	8,400	396
Bliss and Wetherbee No. 30.....	2,153		19,500	1,075
Bliss and Wetherbee No. 30.....	2,112		21,920	618

* Similar to water from the 4,200-foot gas horizon at Cotton Valley and not as salty as that from the 3,600-foot Pine Island oil zone.

FUTURE PRODUCTION

Bellevüe at present (April 1, 1928) is producing 1,120 barrels from 302 wells, or an average per well of 3.7 barrels.[1] Many of these wells are approaching their economic limit, but Nacatoch production at Bellevue should continue for 8 more years. Decline curves drawn for the field indicate that an additional 1,500,000 barrels, with the present production methods, will be obtained, making a total production for the field of 10,000,000 barrels or an ultimate acre-yield of 12,200 barrels.

PRODUCTION AND DRILLING METHODS AND COSTS

Most of the wells at Bellevue were drilled with small portable cable-tool rigs or spudders, although some have been drilled with rotary rigs.

[1] Subsequent note. On May 4, 1929, the field produced 670 barrels from 240 wells, or an average per well of 3.17 barrels.

The wells are pumped from central power plants, or by individual pumping units when the amount of fluid to be handled is excessive. Rod lines from standard units are extended to pumping jacks at some wells.

TABLE VII

ACRE-YIELD OF LOUISIANA-ARKANSAS FIELDS TO JANUARY 1, 1928

Field	Productive Acres	Acre-Yield (in Barrels)
Northern Louisiana		
Bellevue	820	10,360
Homer	2,500	22,454
Haynesville	7,060	7,366
Cotton Valley	2,250	4,436
Bull Bayou	11,000	4,417
Caddo	32,000	3,748
Urania	2,500	3,091
Elm Grove	1,200	1,482
Arkansas		
Smackover	21,360	11,493
El Dorado	8,160	5,376
East El Dorado	1,420	5,100
Irma (Nevada County)	900	2,933
Stephens	2,100	1,606
Lisbon	2,700	1,414

TABLE VIII

PRODUCTION OF OIL FROM BELLEVUE BY YEARS

Year	Barrels	Daily Average (Barrels)
1922	1,479,985	4,110
1923	2,250,057	6,490
1924	1,912,787	5,320
1925	1,212,724	3,370
1926	807,689	2,220
1927	495,265	1,375
1928 (January-March)	96,615	1,062

At present less than 2 per cent of the handled fluid is oil; consequently, the treating of the oil is an important factor in the cost of production. At first the ordinary cooking-vat was used in treating, but now the oil is usually run through gun barrels and then into stock tanks. Tret-o-lite and

sludge soap are used in the treatment. The Gulf Refining Company uses an electrical dehydrator.

Production costs range from \$0.70 to \$1.00 per barrel, although the average cost about four years ago was \$0.26. During the early history of the field some of the wells were blown with air to increase the production. Now the Standard Oil Company and R. L. Autrey are using a vacuum in recovering the oil, and the other operators are using the ordinary pumping methods.

The field is served by two pipe lines: the Standard Oil Company of Louisiana has an 8-inch line to a loading-rack on the Louisiana and Arkansas Railroad at Princeton, and the Louisiana Oil Refining Corporation has a 6-inch line to a loading-rack at Drake on the same railroad.

KEVIN-SUNBURST FIELD, TOOLE COUNTY, MONTANA[1]

W. F. HOWELL[2]
Russell, Kansas

ABSTRACT

The Kevin-Sunburst field is in Toole County, Montana, near the Canadian border. This northernmost field in the United States ranks second in oil production in the Rocky Mountain region. The producing structure is a dome on the north-plunging end of the Sweetgrass arch. The principal oil-producing horizon is at the unconformable contact of the Ellis (Jurassic) and the Madison (Mississippian) limestones. The principal gas-producing horizon is the Sunburst sand (Lower Cretaceous). Although there is no oil production on the top of the dome, it is believed that local folding in areas of porosity has influenced accumulation. The nature of the unconformable contact at the principal producing horizon also affects accumulation.

ACKNOWLEDGMENTS

The writer is indebted to the Marland Oil Company of Colorado, to A. E. Brainerd for assistance in revising this paper, and to B. Rixleben for assistance in the field.

LOCATION

The Kevin-Sunburst field is in Toole County, Montana, 20 miles north of Shelby and 15 miles south of the Canadian boundary. It is on a large dome on the north-plunging end of the Sweetgrass arch. The Sweetgrass arch is approximately 70 miles broad and extends from central Montana northward across the Canadian border. The dips on the arch are very gentle. Because of the low dips, the possibility of obtaining oil on this arch was for a long time disregarded by students of Rocky Mountain geology.

Kevin-Sunburst is the northernmost oil field in the United States. It ranks second in production in the Rocky Mountain area. The production for the week ending August 25, 1928, was 8,000 barrels a day.

Two other areas which offer possibilities as fields, Bannatyne and Pondera (Fig. 1), were opened on the Sweetgrass arch in 1927. The nearest large field is at Cat Creek, 250 miles southeast.

[1] Presented by title before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, July 17, 1928. Published by permission of the Marland Oil Company of Colorado.

[2] Phillips Petroleum Company.

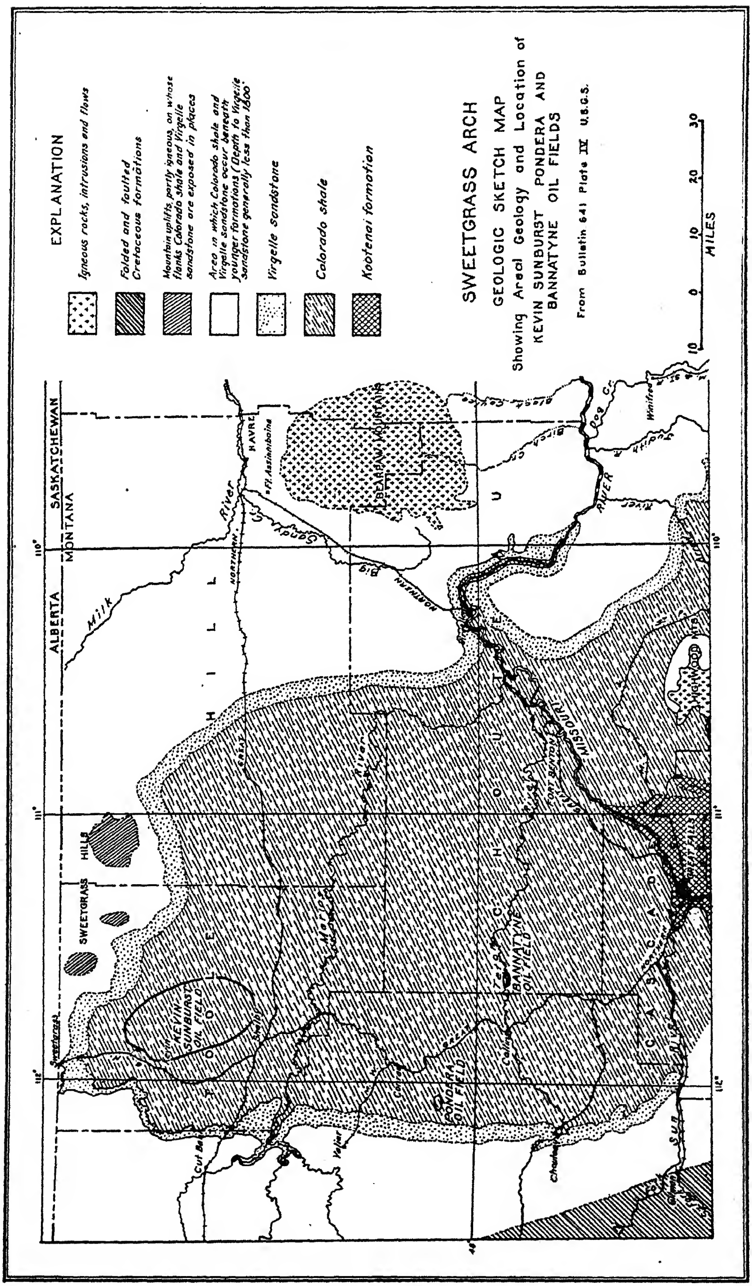


FIG. 1.—Geologic sketch map of Sweetgrass arch, showing areal geology and location of Kevin-Sunburst, Pondera, and Bannatyne oil fields.

HISTORY

As early as 1916, Eugene Stebinger[1] pointed out the possibility of obtaining oil from the Sweetgrass arch. Since the discovery in 1922, reports on the field have been published by A. J. Collier,[2] Frank R. Clark,[3] Dorsey Hager,[4] and by A. J. Collier and W. W. Boyer.[5]

The first well in the Kevin-Sunburst field was drilled in Sec. 16, T. 35 N., R. 3 W., by the Gordon Campbell-Kevin Syndicate. This well was completed March 14, 1922. The well was drilled to the Ellis-Madison contact at a depth of 1,770 feet and produced 5–10 barrels of oil of a gravity of 30° Bé. The well was deepened to 2,540 feet and was abandoned. This well may truly be considered the discovery well because it led to the later development.

The first commercial well in the field was drilled by the Sunburst Oil and Gas Company in Sec. 34, T. 36 N., R. 2 W. It was completed June 5, 1922, in the Sunburst sand at a depth of 1,545 feet. The initial production was 100 barrels of 36° Bé. oil. This well is still producing. Both wells are located northwest of the center of the Sunburst dome.

In areal extent the Kevin-Sunburst is one of the largest producing fields. The area containing oil wells covers approximately 85 square miles; and the surrounding area yielding gas with showings of oil, approximately 180 square miles. The producing area is not continuous, and there are many dry holes throughout the proved area.

To date, three separate areas have produced most of the oil. The first area comprises a group of wells in Secs. 4 and 9, T. 35 N., R. 2 W. In this group, there have been a few large wells. An illustration is the Ohio's Baker No. 3, completed March 19, 1923, with an initial flow of 1,500 barrels a day. This well has produced up to April, 1927, more than 400,000 barrels of oil. A diagonal offset has produced 275,000 barrels. These two wells soon settled to small producers, but they have had a rather steady settled flow. The surrounding wells are small but are producing satisfactorily.

[1] "Possibilities of Oil and Gas in North-Central Montana," *U. S. Geol. Survey Bull. 641-C* (1916).

[2] "The Kevin-Sunburst Oil Field, Montana," *U. S. Geol. Survey Press Notice 13,466* (September 7, 1922).

[3] "Notes on the Kevin-Sunburst Oil Field, Montana," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), pp. 263–76.

[4] "The Sunburst Oil and Gas Field, Montana," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 69 (1923), pp. 1101–19.

[5] "The Kevin-Sunburst Oil Field, Montana," *U. S. Geol. Survey Press Notice 2,655* (January 12, 1926).

The second group, or Shoshone pool, was developed in Secs. 4 and 5, T. 34 N., R. 2 W. Several wells in this group had initial flows of 5,000 barrels per day, but the decline was very rapid and at present the group is producing only a small amount of oil with a large amount of water.

The third group, or East pool, lies in Secs. 29, 30, 31, and 32, T. 35 N., R. 1 W., and in the east half of Sec. 36, T. 35 N., R. 2 W. This area has proved to be the most productive; in fact, the greatest part of the field's production has come from the East pool. There are very few dry holes in this area, and several wells have been completed with an initial production of 5,000 barrels per day. The area has been almost completely drilled, although a few edge wells may be added.

Between these three areas, there are some good wells from which considerable oil has been produced. The top of the Sweetgrass arch has been tested dry.

STRATIGRAPHY

PLEISTOCENE

Glacial.—In places, there is a thin surface covering of glacial material, left by the invasion of the Montana lobe of the Keewatin ice sheet.

CRETACEOUS

Eagle sandstone.—The Eagle sandstone, a massive sand of Cretaceous age, borders the field on the west, north, and east sides. On the west, the Virgelle sand (basal Eagle) forms a prominent escarpment.

Colorado shale.—Underlying the Eagle sand is the Colorado shale (Middle Cretaceous), which crops out throughout the area of the field (Fig. 2). This is a thick massive shale of dark color; the upper half contains no sands and only a few concretionary beds; the lower half has several lenticular sands, some of which carry water and gas with showings of oil. One of these sands is very persistent throughout the north part of T. 35 N., R. 2 W., and in that area ordinarily carries water, thus necessitating an extra string of casing. The shale has a total thickness of 1,750 feet. The amount of Colorado shale encountered in the wells ranges from approximately 700 feet on top of the structure to almost the total thickness on the west side of the field.

Kootenai formation.—Underlying the Colorado shale is the Kootenai formation of Lower Cretaceous age, a fresh- or brackish-water deposit. This formation has a thickness ranging from 350 to 400 feet and is composed of red and variegated shales, with some sands. Near the base is the Sunburst sand, a producing horizon, whose thickness ranges from 5 to

50 feet. The top of the Kootenai is not everywhere red but can be easily differentiated from the typical overlying dark Colorado shale.

At the base of the formation, and just below the Sunburst sand, is yellow shale ranging from 10 to 30 feet in thickness. This shale occurs throughout the greater part of the field and is the best marker for corre-

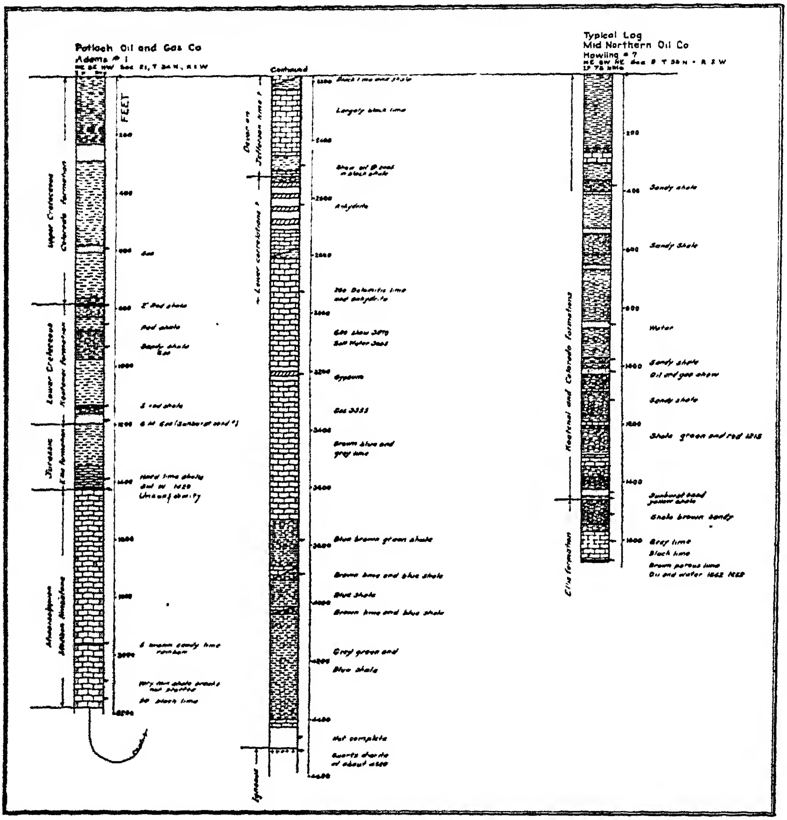


FIG. 2.—Stratigraphy of Kevin-Sunburst field, as shown by well logs.

lation purposes. It is not logged in several wells in T. 35 N., R. 3 W., and it is not present in parts of T. 34 N., R. 1 and 2 W.

The Kootenai formation is coal-bearing in a large part of Montana and in Alberta on the north but does not carry coal in the Kevin-Sunburst field.

JURASSIC

Ellis formation.—The Ellis formation of Jurassic age underlies the Kootenai. It is of marine origin and has a thickness of 200–250 feet.

The average interval from the top of the Sunburst sand to the Ellis-Madison contact is 230 feet in the north part of T. 35 N., R. 2 W; 6 miles south in the Shoshone group of wells the interval has thickened to approximately 255 feet.

There is some evidence of a slight unconformity between this formation and the overlying Kootenai, and the Ellis is known to rest unconformably on the Madison limestone. The long period of erosion occurring before Ellis deposition suggests a very pronounced disconformity between the Ellis and Madison formations. This disconformity, however, is not as evident as would be expected, probably because the surface of the limestone was practically base-leveled before Ellis time. At the base of the formation, there is 100–150 feet of black, limy shale which is ordinarily logged by the drillers as "black lime."

At the contact between the Ellis and Madison lies the so-called "Ellis sand," (in most places, porous Madison), the principal producing horizon.

CONGLOMERATE

Near the Little Rocky Mountains, a 4-foot chert conglomerate or breccia lies on the Madison limestone, immediately beneath the Ellis shales. This breccia is composed of angular residual material derived from the top of the Madison, or it may be accumulated residuum from erosion of younger beds. This breccia is very probably present in the field, and a large part of the chert encountered with the "pay" may come from this horizon.

One well in Sec. 2, T. 34 N., R. 2 W. encountered at the contact considerable unconsolidated material composed of chert and rounded limestone pebbles. A puff of gas caused this material to bulge up the hole a distance of 50 feet.

The age of this conglomerate is questionable. It may be of Mississippian age or it may be later.

MISSISSIPPIAN

Madison limestone.—The Madison limestone of Mississippian age underlies the Ellis. It is a massive white to blue lime with a thickness of 780 feet. There is no sand in the formation, but there are horizons that carry water. These water horizons are ordinarily pulverized in drilling, the cuttings of lime resembling very fine sand and commonly being logged as such. The upper part of the lime is dolomitic.

Very few wells have produced in the upper part of the Madison below the contact zone. The average thickness of the Madison limestone at the outcrop in the adjacent mountain areas is approximately 1,200 feet. If

the thinning over the Sweetgrass arch is due to continued erosion, approximately 400 feet of Madison must have been removed.

DEVONIAN

Jefferson limestone.—Below the Madison lime there is 355 feet of impure limestone, with some dark shale, which has been correlated with the Jefferson of Devonian age.

These black shales were found to be petroliferous in Sec. 21, T. 34 N., R. 1 W., in a diamond-drill hole.

LOWER FORMATIONS

Correlations below the Jefferson lime are questionable. The deepest well in the field was drilled to a depth of 4,520 feet. This well, located in Sec. 21, T. 34 N., R. 1 W., encountered a quartz diorite at approximately 4,500 feet.

Approximately 275 feet of anhydrite and gypsum below the Jefferson limestone has been classified by F. C. Platt as of probable Silurian age.

Below the anhydrite, Platt mentions 900 feet of dolomitic limestone, anhydrite, and shale, as having been tentatively correlated with the Ordovician.

The remaining 680 feet of green-gray and blue-gray shale that rests upon the diorite is considered as of probable Cambrian age.

STRUCTURE

The structure of the field is that of a large dome with some irregular minor folding. The subsurface structure-contour map shows a closure of 600 feet. The closure is known to be several hundred feet more, as the flank dips continue several miles beyond the limits of the map.

The surface structure conforms in a general way with the subsurface. Because of lack of outcrops that can be used as key beds, it is impossible to map the surface structure in much detail, though the general structure is apparent, and was mapped in 1921.[1]

The subsurface map was contoured on the Ellis-Madison contact as a datum (Figs. 3 and 4). This datum was used because of its importance as a producing horizon. In wells that encounter no oil, the decided lithologic change between the overlying black Ellis shale and the Madison limestone ordinarily is accurately logged.

In reality the map shows, in detail, the present buried surface topography of the Madison lime. This surface, as would be expected, is irregular. The Madison limestone (Mississippian) was unquestionably sub-

[1] Dorsey Hager, *op. cit.*

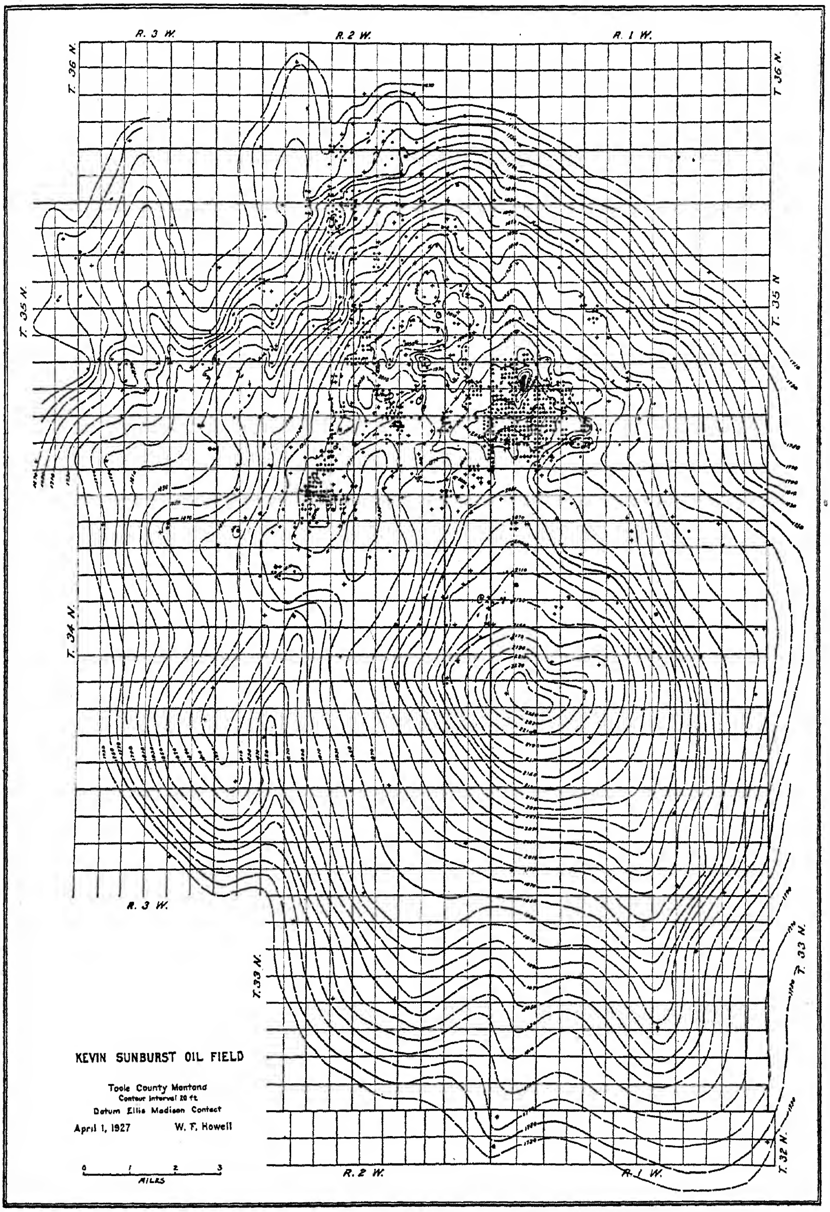


FIG. 3.—Subsurface structure of Kevin-Sunburst oil and gas field, contoured on Ellis-Madison contact. Contour interval, 20 feet. The principal gas area is on the south flank of the large dome.

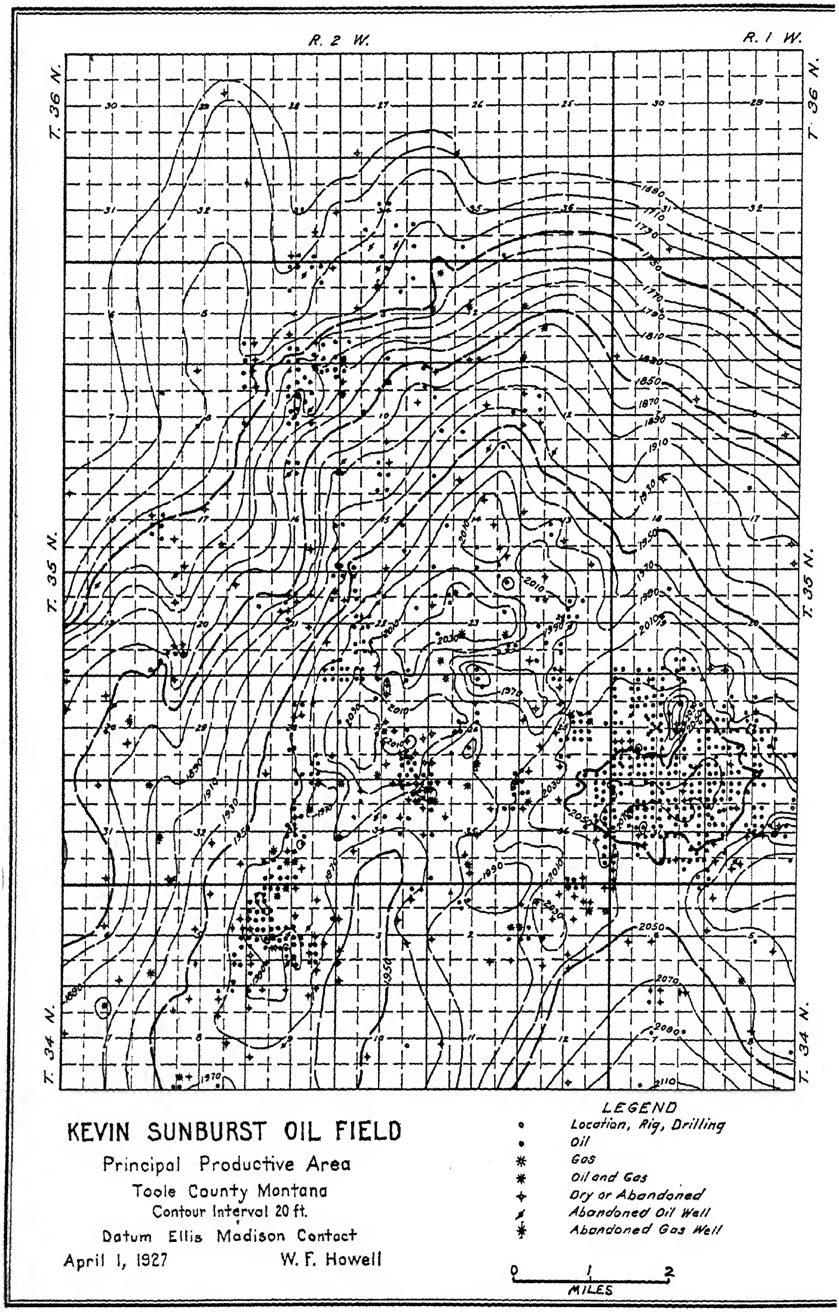


FIG. 4.—Structure of principal productive area, Kevin-Sunburst field, contoured on Ellis-Madison contact

jected to a long period of erosion before the later period of Ellis (Jurassic) deposition. As judged by the thickness of the Madison lime, shown by the section made southeast of Great Falls, the formation was subjected to an erosion of approximately 400 feet on the arch. The section at Great Falls has a thickness of approximately 1,200 feet, although several wells that have penetrated the Madison on the Sweetgrass arch show it to have a thickness of only 800 feet.

UNCONFORMITIES

A map drawn on the Sunburst sand as a datum closely conforms in structure with one on the Ellis-Madison contact datum. There are very minor structural differences that suggest a slight unconformity between the Kootenai and the Ellis formations. The unconformity between the Ellis and the Madison will be discussed later in more detail.

RELATION OF STRUCTURE TO ACCUMULATION

There is no oil production on top of the structure, but a study of the map indicates that local structure in areas of porosity has a decided effect on accumulation. The East pool has a closure of 40 feet or more and is located on a pronounced nose, plunging northward from the main "high."

The Shoshone pool is located on a narrow, irregular fold. Although structure is an important factor in accumulation, there are other controlling factors upon which it is dependent.

As mentioned elsewhere, the Sunburst sand does not carry water but is dry throughout the field. In this connection, it is interesting to note that the Sunburst oil production comes from areas situated very low structurally. One well in the center of Sec. 13, T. 35 N., R. 3 W. is in the bottom of a pronounced plunging syncline.

In the SW. $\frac{1}{4}$, SW. $\frac{1}{4}$, SE. $\frac{1}{4}$ of Sec. 23, T. 35 N., R. 2 W., is a Sunburst sand well, and the south offset also is producing from the same horizon. Both are very low structurally as compared with surrounding wells.

Two other Sunburst areas may be classed as edge production, but in these areas the Ellis also is productive and a few wells produce from both horizons.

The factors other than structure which have affected accumulation are amount of porosity and nature of contact zone, as well as the unconformity itself and a variable condition of water saturation.

FAULTS

There is no surface evidence of faulting, and a careful study of all the well logs shows no faults with appreciable throw.

Many exceptional and freak conditions in this field have been explained by some geologists as the result of a faulted condition. Near the central part of the arch, there are two long areas showing steep dips which were interpreted by some as surface faults. The first maps of the field showed these features as faults, with a northwest strike. Later, they were believed to be the results of glaciation, the latter belief being now more commonly accepted. Since this fault theory has been accepted by some geologists, a few of the reasons for the belief, with an explanation for the occurrence, are here given: (1) offset wells producing from different levels and in reality from different horizons but assumed to be the same horizon; (2) differences in production of offset wells, the result of difference in sand porosity and lack of uniform saturation rather than the result of faults; (3) large gas wells, situated very low structurally, mentioned elsewhere in this paper, caused probably by lenticularity and difference in porosity of the sand; (4) differences in color and character of the top of the Kootenai, the red shale streaks not being constant, thus resulting in confusion where markers in the Kootenai have been used as a datum; and (5) shale slumping or weathering of a peculiar type that has been mistaken for surface evidence of faulting.

WATER LINE

The field has no definite water line, and there is no uniform water saturation. This is the result of non-uniform porosity of the pay horizon, influenced by the unconformity.

It is interesting to note that the amount of water produced with the oil from some leases with settled production varies in amount from month to month. There is no uniform rate of decline or increase; some months it is more and some less than the preceding month.

Sulphur water produced from the upper Madison "breaks," and that from the Ellis-Madison contact are similar, and it is impossible to differentiate one from the other by analysis.

OIL AND GAS HORIZONS

Colorado shale.—In the lower Colorado shale, there are lenticular sands that in places carry some showing of oil and gas.

Sunburst sand.—Near the base of the Kootenai formation lies the Sunburst sand. This sand is the principal gas-producing horizon of the field and produces some oil. It is irregular in thickness and character, the thickness ranging from almost nothing to 75 feet. It is a true white quartz and in places is slightly conglomeratic, composed in part of very small pebbles.

The gas wells vary in size from a few thousand to 14,000,000 cubic feet. It is significant that the largest gas wells are situated low structurally, and south of the main "high." The Saint Paul–Montana Cox well in Sec. 34, T. 33 N., R. 2 W. is a 14,000,000-foot gas well, and is 522 feet lower structurally than the highest well drilled. Several other gas wells have been drilled in this vicinity at almost the same structural position. These wells are larger and more consistent producers than others higher on structure. This large volume of gas so low structurally can be explained only by the lenticular nature of the sand or its irregular porosity.

The sand is uniformly dry throughout the field, and the oil and gas produced are free from sulphur and water. This sand does, however, carry water in the vicinity of Shelby and Virden, where salt water is reported in at least three wells.

The Sunburst oil is free from sulphur and is of higher gravity than the Ellis oil. Its gravity is approximately 36° Bé. Only a small amount of oil is produced from the Sunburst, and the wells are small, with maximum initial production of 100 barrels.

The principal area producing oil from the Sunburst sand lies in Secs. 33, 34, and 35, of T. 36 N., R. 2 W., and in Secs. 3 and 4, T. 35 N., R. 2 W. Other producing areas are very small, with not more than three or four wells in a group.

Stray horizons in the Ellis formation.—A few good wells have encountered oil above the normal Ellis "pay." These horizons are irregular sand lentils ordinarily found from 30 to 80 feet above the Ellis-Madison contact. The oil is of higher gravity than either the Ellis or Sunburst oil and is free from sulphur. Large wells producing from this horizon are commonly offset by wells that fail to find production in the same stray.

Ellis sand.—The so-called "Ellis sand" is the principal producing horizon of the field. This productive zone lies at the contact of the Ellis and the Madison, and in most places at the extreme top of the Madison.

In reality, this pay horizon is not a sand but rather a broken, weathered, discolored lime, which in places is very cherty with some secondary silica. The character of this zone is highly variable, and thickness and porosity of the "pay" in a given well ordinarily determine the size and life of the well.

There are areas where wells are drilled through the black Ellis lime into the white Madison lime without encountering either oil or water. This lack of production is due to the absence of porosity at the contact. In these areas, the black Ellis lime seems to have been deposited on the Madison, where the surface was less affected by weathering; and since

deposition this contact has remained impervious, thus preventing a circulation of water, as is evidenced by the lack of secondary material. The absence of oil production on the south flank of the structure can be explained in this way. In this area it is necessary to drill into the Madison to depths ranging from 20 to 70 feet before water is encountered.

Why this contact should be so irregular in character, and the horizon have greater porosity in the area on the north and northwest sides of the structure, is a question worthy of consideration. The erosional unconformity at the contact, the non-uniform character of the chert conglomerate between the Ellis and Madison formations, also the irregular Madison surface, varying in both composition and topography, are conditions that have prevented a uniform saturation of either oil or water. These conditions are suggested as contributing factors to account for the variable character of this contact zone.

The oil produced from the Ellis has an average specific gravity of 30° Bé. It has a slight sulphur content, and in several localities considerable sulphur water is produced with the oil.

Very few wells have encountered much gas at the contact. One well drilled by the California Company in the NE. $\frac{1}{4}$, NW. $\frac{1}{4}$, NW. $\frac{1}{4}$ of Sec. 26, T. 35 N., R. 2 W., had an initial production of 8,000,000 cubic feet. The ordinary production of other Ellis gas wells in this vicinity varies from 1,000,000 to 2,000,000 cubic feet; however, gas wells of 1,000,000 feet or more are exceptional.

The average drilling depth to this horizon ranges from 1,400 to 1,800 feet, dependent upon the structural position of the well. Initial production varies from a few barrels to more than 5,000 barrels a day.

Stray horizons in the Madison limestone.—Undoubtedly considerable oil is produced from the top or upper 6–8 feet of weathered Madison lime, which may rightly be considered as coming from the normal contact zone.

In Sec. 27, T. 35 N., R. 2 W., three or four large wells were completed at different depths in the Madison. The first of these, the O'Neil-Lashbaugh No. 1, located in the SW. $\frac{1}{4}$, SE. $\frac{1}{4}$, SE. $\frac{1}{4}$ of the section, found a small amount of oil and water at the contact but failed to produce after a shot. At a depth of 50 feet in the Madison, production was found and for several weeks continued at the rate of 2,000 barrels a day. This well later sanded (?) up and has been abandoned.

This well was a direct offset to another 1,400-barrel well that produced from a stray sand in the Ellis, 45 feet above its base. Both were large wells, neither producing from the normal pay horizon and one producing from a "pay" 95 feet lower in the section than the other.

In this group of wells, one found production 80 feet in the Madison and another is reported to be producing from a depth of 100 feet in the lime. The adjacent wells are normal contact wells, and this stray horizon probably is not the same in any two of the three wells inasmuch as several adjacent wells drilled to this horizon have failed to find production. Samples of the "pay" show it to be a soft streak in the lime and to contain no sànd. Calcite veins occur in the soft lime, indicating the possibility of fracturing.

A small amount of production has been encountered in Sec. 18, T. 34 N., R. 1 W., at depths ranging from 20 to 30 feet in the Madison. It is doubtful if this production is of commercial value.

TABLE I

COMPLETED WELLS, KEVIN-SUNBURST FIELD

	Year					Total	Status		
	1922	1923	1924	1925	1926		Dec. 31, 1925	Dec. 31, 1926	Dec. 31, 1927
Oil wells	26	104	80	228	229	667	424	650	860
Gas wells	4	5	5	17	34	65	31	65	98
Dry holes	15	73	47	106	127	368	241	368	498
Oil wells (abandoned)	....	.....	.....	.....	.....	....	14	17	....
Total	45	182	132	351	390	1,100	710	1,100	1,456

No other production from the Madison is known, except possibly one well on the Big West lease in Sec. 31, T. 35 N., R. 1 W. Five wells have been drilled through the Madison, none of which has encountered commercial production below.

The oil occurring in the Madison lime, at isolated places and in irregular horizons, probably had a common origin with the Ellis oil above. It seems probable that this oil filtered down through permeable, partly filled sinks and accumulated in caverns or soft permeable streaks in the Madison lime. The existence of sinks and underlying caverns in the Madison is suggested by the long period of erosion before Ellis deposition.

DEVELOPMENT

The figures in Table I indicate the steady development of the field. These figures were taken from F. C. Platt's commercial scout report.

PRODUCTION

Oil.—The production of the field has increased yearly, and reached its peak in July, 1926; during this month, the daily average production

was 25,780 barrels. During 1927, however, there was a very decided decline, for with 110 new wells the daily average was 6,195 barrels less than in 1926. A still further decline of 3,000 barrels a day is noted in 1928. At present, September, 1928, the field is producing approximately 8,000 barrels daily, and production probably will be maintained near this figure for some time.

The figures in Table II, taken from C. E. Shoenfelt's report, indicate the increase by years; they do not include oil used for fuel.

TABLE II

PRODUCTION INCREASE, KEVIN-SUNBURST FIELD

Year	No. Producers Completed	Barrels Produced	Daily Average
1922	22	28,987	79
1923	104	417,928	1,145
1924	80	1,206,050	3,295
1925	228	2,716,040	7,441
1926	229	6,479,892	17,753
1927	110	4,218,823	11,558
Total	....	15,067,720	....

It is very difficult to estimate ultimate production in this field, owing to erratic differences in initial production and decline rates. Decline rates for offset wells vary greatly.

Gas.—On January 1, 1927, there were sixty-three commercial gas wells that are estimated to have had an initial capacity of 190,000,000 cubic feet. This does not include gas developed in commercial oil wells.

This gas, both from the Ellis and the Sunburst, is dry. The Sunburst gas has 1,050 B.T.U., and the Ellis has 925 B.T.U., per cubic foot.

Gas is used extensively in the field as fuel for drilling. The towns of Shelby, Sunburst, Kevin, and Oilmont are supplied with gas from the field. The local refineries are also supplied with this fuel.

The south flank is capable of producing a large volume of gas, and it is probable that a pipe line will eventually connect this area with Great Falls.[1] At present (1927) several wells are drilling in the area of the Sweetgrass Hills, and these wells may develop sufficient additional gas to make practical the construction of such a line.

[1] The Northern Natural Gas Development Company built a gas line to Great Falls in 1928—EDITOR.

NEW YORK OIL FIELDS[1]

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ABSTRACT

The oil fields of New York represent the extreme northeastern extension of the Appalachian oil fields. The most westerly New York pool is located in Cattaraugus County and is in reality the northerly continuation of the Bradford pool of Pennsylvania. At the east, and confined to Allegany County, is the Richburg pool, the largest and most productive in the state. Several smaller pools occur—among them the Marsh pool in Steuben County, which, with the exception of the Gaines oil pool in Pennsylvania, is the most easterly producing pool in the United States.

The productive sands of New York are all of Devonian age. The oil region is a dissected plateau, and depth of wells in the main sands ranges from about 900 feet in the valleys to more than 2,000 feet in the uplands. There is a slight regional southwest dip, and a few low anticlines and synclines have been recognized. Several types of sand are found, though on the whole the sands are fairly persistent. The presence of oil in synclines and the absence of salt water from most parts of the fields are noteworthy features.

The total production of oil since the development of the fields nearly fifty years ago is 75,000,000 barrels. The wells are small and yield oil slowly; one well that was drilled in 1879 is still being pumped.

During the last twenty-five years there has been no important lateral extension of the pools, nor have deeper producing sands been discovered. The present annual production is more than double that of ten years ago. Increase in production during recent years is due largely to flooding methods by which hydrostatic pressure on the oil sand is maintained through the use of water wells.

INTRODUCTION

The New York oil fields are in the southwestern part of the state in the three counties of Cattaraugus, Allegany, and Steuben (Fig. 1). On the south, each of these counties borders Pennsylvania. In Cattaraugus, the westernmost of the three, is the northern extension of the Bradford field of Pennsylvania. At the east, and situated entirely in Allegany County, 9 miles distant from the Bradford pool, is the Richburg pool, the largest and most productive in the state. In this county, too, is the Scio pool, the most northerly producing pool of the Appalachian field. East of the Richburg pool are several small pools, of which the Marsh pool in Steuben County near its western border is the last producing pool at the east.

[1] Presented by title before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, December 9, 1927. Published by permission of the director, New York State Museum, Albany, New York.

[2] Assistant state geologist.

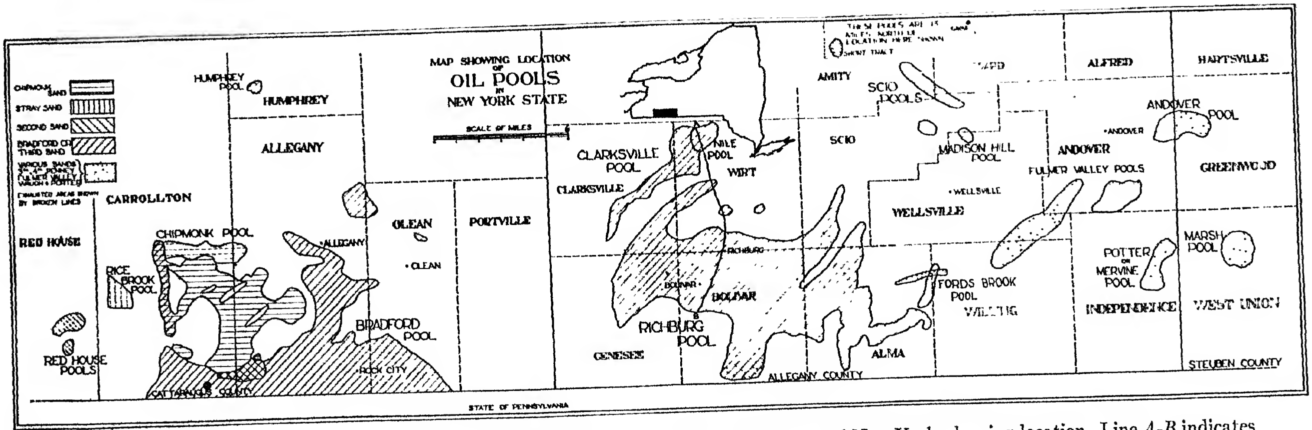

FIG. 1.—Oil fields of Cattaraugus, Allegany, and Steuben counties, with insert map of New York, showing location. Line *A-B* indicates section through Nile-Richburg pools.

With the exception of the Gaines pool in Pennsylvania, the Marsh pool is the most easterly producing pool in the United States. The Marsh pool lies 25 miles north and 7 miles west of the Gainesville pool.

Altogether the oil pools of the state comprise about 50,000 acres and may all be included in a rectangle 54 miles long east and west and extending 12 miles north from the New York–Pennsylvania state line.

PHYSIOGRAPHY

The New York oil fields lie within the northern border of the Allegany plateau, which constitutes the westernmost physiographic division of the Appalachian province as developed in Pennsylvania. The oil fields are approximately 60 miles from the distinctly folded ridges of the Allegany Front. West of the Allegany Front, folding becomes less and less pronounced; and in the oil regions only gentle undulations are found, and these do not have any clearly marked effect on the topographic features. Eastward from the oil fields, the stratigraphic series continues in New York as a plateau without any faulting and with only slight undulations which finally merge into the Catskill mountain plateau approximately 200 miles away. North of the oil region, the country descends to the level of Lake Ontario (247 feet above sea-level), a distance of about 75 miles. Owing to the southerly dip of the strata, the northern outcropping edges of the underlying formations including the Medina sandstone and shale along Lake Ontario are exposed at several places. Several oil springs occur just beyond the northern border of the productive fields. Among these is the famous Cuba oil spring known since early Colonial time and one of the sources of the Seneca oil of the Indians.

The plateau constituting the oil region has been deeply dissected by streams, as exemplified by the horseshoe bend of Allegany River and the Genesee. The region therefore belongs to two major drainage systems, namely, the Allegany-Mississippi and the Genesee–St. Lawrence. Because the region is a dissected plateau, the depth to the producing sands ranges from approximately 800 feet in the valleys to more than 2,000 feet on the uplands. In the greater part of the oil region the elevations range from 1,600 to 2,500 feet above sea-level.

With the exception of the territory south of the terminal moraine, the oil regions are rather heavily mantled by glacial drift, and throughout much of the glaciated territory rock outcrops are scarce for a region of such marked relief. As a result of glacial stream and lake deposits even south of the terminal moraine, many of the pre-glacial valleys are deeply filled, and the courses of some of the streams, including Allegany River,

have been greatly changed. In Allegany County, only a part of the southern spur of the Richburg pool is south of the terminal moraine, and in Cattaraugus County, only the northern spur of the Bradford pool lies north of it. The depth of the glacial material is extremely variable. In some of the stream-filled valleys, the depth from the surface to bed rock is as much as 300 feet, and 100 feet of drift is not of uncommon occurrence. In the uplands the glacial material is much thinner, and in many places the bed rock is less than 30 feet from the surface.

HISTORY

Although the Cuba and other oil springs lying north of the present producing oil fields were known for many years, no systematic efforts to drill an oil well were made until 1864, five years after the Drake well had been completed in Pennsylvania, when a well was drilled at Limestone, Cattaraugus County. In 1866, a well was drilled at Whitesville, Allegany County. Neither of these wells proved productive. They were drilled in hope of finding the sand which was producing oil in Pennsylvania; and in the early attempts there was little to guide the drillers in a geological way, outside of a general knowledge that the strata were nearly horizontal and that the Pennsylvania formations must reasonably be expected to extend into New York, as had been pointed out by the early geological surveys.

Following the development of the Bradford pool in Pennsylvania, wells were drilled in rapid succession in the New York section of the pool, and by 1878 there were 250 producing wells in the Cattaraugus County field. In Allegany County, after several wildcat tests, a successful well was completed in 1879 in the town of Scio. This well was drilled by O. P. Taylor and is locally known as Taylor's discovery well, or Triangle No. 1. The oil sand was found from 1,126 to 1,153 feet, and the well was finished at 1,177 feet. A remarkable feature of this well is the fact that although it had an initial production of but 8 or 10 barrels, it is still being pumped after a period of more than forty-eight years. The well log for Triangle No. 1 is given in Table II. Following the drilling of the Triangle well, the oil territory was rapidly developed; and in 1881 a well was drilled at Richburg with an initial production variously estimated from 300 to 400 barrels. The flush period was in the early eighties, with an annual production in the state of more than 5,000,000 barrels. Following the period of flush production, the drilling of additional wells did not stem the gradual decline in production, nor have any important new pools been discovered. In 1912, only 782,661 barrels were produced. With the introduction of

flooding methods now being regularly employed in most of the New York oil fields, the annual production has recovered to a considerable extent and has doubled in amount as compared with its total ten years ago.

STRATIGRAPHY

COLUMNAR SECTION

In the columnar section (Table I) is given the stratigraphic succession in western New York. None of the rocks below the Chemung formation is exposed in the area of the oil fields. The thickness and the character of the lower formations are determined from deep wells and from numerous outcrops at the north. In western New York the thicknesses of the formations below the Medina are known only from well records. The lower formations which yield gas are noted in the table.

EXPOSED BEDS

Olean conglomerate.—With the exception of a few feet of Sharon shale overlying the Olean conglomerate at Rock City and containing a thin coal bloom, the Olean constitutes the highest member of the New York Paleozoic series. The main mass of this conglomerate forms the surface rock in the section of the Bradford pool lying south of Olean along the Pennsylvania border. Wells commenced on the Olean conglomerate reach the main Bradford sand at depths ranging from 1,700 to 1,800 feet. This formation is characteristically a massive round-pebble conglomerate, although locally its texture changes within short distances both horizontally and vertically, being strongly cross-bedded. Most of the pebbles in the conglomerate are well rounded and occur as large as 3 inches in diameter, although the average diameter is much less. The round shape of the pebbles distinguishes this formation from underlying conglomerates which have flat or discoidal pebbles.

The Olean conglomerate weathers rather rapidly, and massive detached boulders broken off along joint planes form the well-known Rock City near Olean. The character of the surface of the formation is illustrated in Figure 2.

Oswayo beds.—These beds range in thickness from 160 to 250 feet and are composed of olive-green and rusty-colored sandy shales with thin seams or incrustations of limonite. The Oswayo contains a marine fauna and the brachiopod *Camarotoechia allegania* is a characteristic fossil. Near the base of the Oswayo is a rather persistent layer of impure limestone 1 foot or 2 feet thick made up largely of fragments of brachiopods and other shells.

TABLE I

GENERAL COLUMNAR SECTION

Group	System		Series	Description	Thickness in Feet
Paleozoic	Carboniferous	Pennsylvanian (Pottsville)	Olean	Coarse conglomerate with well-rounded pebbles mostly of vein quartz. Texture changes in short distances both horizontally and vertically into coarse white sandstone. Approximately 1,700–1,800 feet above main producing oil sands	60–70
			Unconformity	Absence of the Mauch Chunk and associated formations. 4,000+ feet	
		Mississippian (Bradford)	Oswayo	Fossiliferous olive-green and rusty-colored limonitic shales. Near base, bed of very fossiliferous limestone 2 feet thick. A probable small unconformity between the Oswayo and Cattaraugus. Few thin beds of sandstone	160–250
			Cattaraugus	Bright-red shales with interbedded green or bluish shales and fine-grained micaceous sandstones. Local beds of conglomerate characterize the formation. At base is the Wolf Creek conglomerate. All the conglomerates of the Cattaraugus beds have flat or discoidal pebbles, some of jasper, distinguishing them from the Olean	300–350
	Devonian		Chemung	Gray, olive, and bluish shales, some dark purple or chocolate color. Many thin beds of argillaceous sandstone. Lower half of the Chemung contains all the oil-producing sands of the state	1,200–1,500
			Portage	A well-defined series of sandstones, flags, and black carbonaceous shales. Has gas-bearing strata	1,200–1,700
			Hamilton and Marcellus	Blue, gray, and olive shales. Basal portion, the Marcellus black shale, which is gas-bearing	600–700
			Onondaga	Also called "Corniferous." A heavy-bedded limestone, the "flint" of the drillers. Gas-bearing	130
			Unconformity	Absence of Helderbergian formations	

TABLE I—*Continued*

Group	System	Series	Description	Thickness in Feet
Paleozoic	Silurian	Salina	A series of waterlimes, gypseous shales, beds of anhydrite and gypsum, rock salt. Red shales at base. Upper part of series, gas-bearing	700–800
		Niagara	At top heavy-bedded dolomites. Lockport and Guelph. Rochester shale at bottom	200
		Clinton	Limestones, shales, with thin bed of hematite	80
		Medina	Upper 150 feet white and red sandstones. Most prolific gas horizon in state. Main mass is red shale with white Oswego sandstone at base	1,100–1,200
	Ordovician	"Hudson River" and Utica	A series of alternating beds of sandstone and shales. At base is Utica black shale	600
		Trenton	A dark limestone, nearly everywhere containing a little gas, but few long-lived wells found	700–900
		Beekmantown	A heavy-bedded limestone. Also known as the "Calciferous" formation	137
	Cambrian	Potsdam	A sandstone where present directly overlying the pre-Cambrian. Reported in a few deep wells in western New York	?
Pre-Cambrian			Reported in several western New York wells	

Cattaraugus beds.—These beds consist of bright red shales interbedded with greenish and bluish shales and thin beds of fine-grained micaceous sandstones together with two or three well-defined beds of flat pebble conglomerates. Many of the sandstones are cross-bedded and are persistent as individual beds only for short distances. Limonitic concretions in the sandstones contain fish remains, but the shales and sandstones as a whole are nearly barren of fossils. In origin the character of the shales and sandstones suggests the Catskill type of non-marine sedimentation. This phase of sedimentation started in the Catskills and spread toward

the west with progressively higher and higher beds. Near the middle of the Cattaraugus beds is the Salamanca conglomerate containing a marine fauna. It is found only from Cattaraugus County westward, and in the region south of Olean it is about 15 feet thick and is locally known as the Mount Hermon sandstone, a coarse-grained rock containing a few quartz pebbles. The sandstone phase of the Salamanca is characterized by the occurrence in it of many vertical fucoid stems or tubes. The massive conglomeratic character of the Salamanca is best developed at the Salamanca rock city about 17 miles northwest of Olean. Fifty to 70 feet

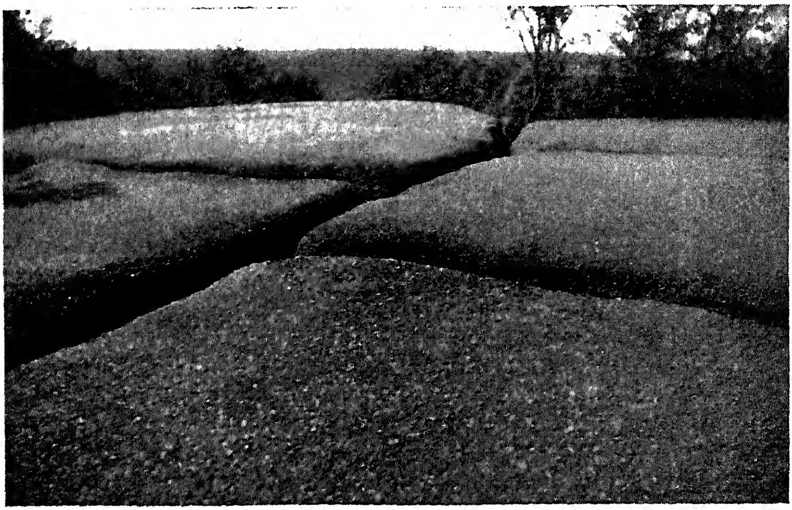

FIG. 2.—Surface of Olean conglomerate at Rock City, south of Olean, showing joint planes.

above the Salamanca, and found only in the western part of the oil fields, is the Kilbuck conglomerate. It has a maximum thickness of not more than 15 feet, and in lithologic features resembles the Salamanca.

The Wolf Creek conglomerate forms the basal member of the Cattaraugus beds. Like the Salamanca and Kilbuck, it is characteristically a flat- or discoidal-pebble conglomerate as distinguished from the round-pebble Olean conglomerate. In size, some of the pebbles range from 1 inch to 2 inches in diameter, but most of them range from about $\frac{1}{2}$ to $\frac{1}{8}$ inch. The main mass of the rock is a coarse cross-bedded sandstone, in places white, but ordinarily stained yellow or brown. In thickness, the conglomerate is extremely variable. From a maximum of 20 feet it may thin

in a few hundred yards to but a few inches, and in much of the district its thickness does not exceed 2 feet, and in some localities may be absent.

The presence of jasper pebbles in the Wolf Creek conglomerate, as well as in the other conglomerate beds of the Cattaraugus, suggests a western origin, possibly from the Lake Superior region, of the pebbles composing these conglomerates. The flat shape of the pebbles indicates transportation for long distances along beaches.

The Wolf Creek conglomerate contains a marine invertebrate fauna. In addition to the pronounced change in conditions of sedimentation following the Chemung, the Wolf Creek marks the introduction of the first Carboniferous type of fossils and for this reason is regarded as the base of the Carboniferous.

Chemung beds.—The Chemung beds, which constitute the highest member of the Devonian in western New York, contain in their lower part all of the producing oil sands of the state. The total thickness of the Chemung is 1,500 feet. The formation consists of many beds of shale and argillaceous sandstone that are extremely variable as lithologic units; and rarely do they maintain their individuality or thickness for any considerable distance. The Cuba sandstone, 15 to 20 feet thick and occurring in the upper part of the Chemung, is probably the most persistent sandstone in the region. Both the sandstones and shales contain a rather plentiful marine fauna. The relative position of the oil sands in the Chemung as far as they have been determined is given in the accompanying diagram (Fig. 3).

LOG OF WELL

The well log in Table II gives in detail the character of the rock in Triangle well No. 1, Lot 4, Town of Scio, Allegany County. The well is located near the eastern edge of the Richburg pool. The mouth of the well is a short distance below the top of the Chemung. The well was drilled in 1879 and is still producing a small amount of oil. The elevation at the mouth of the well is 1,825 feet; at the bottom of the well it is 648 feet above sea-level.

RESERVOIR ROCKS

LITHOLOGY

The oil-bearing sandstones are of a nearly uniform chocolate brown, a few samples showing a grayish tone. They contain fossils, mainly brachiopods, which occur in several of the samples examined. In texture, the sandstones are fine-grained and, in general appearance and hardness, are much like building stones. Thin breaks and films of shale are found in

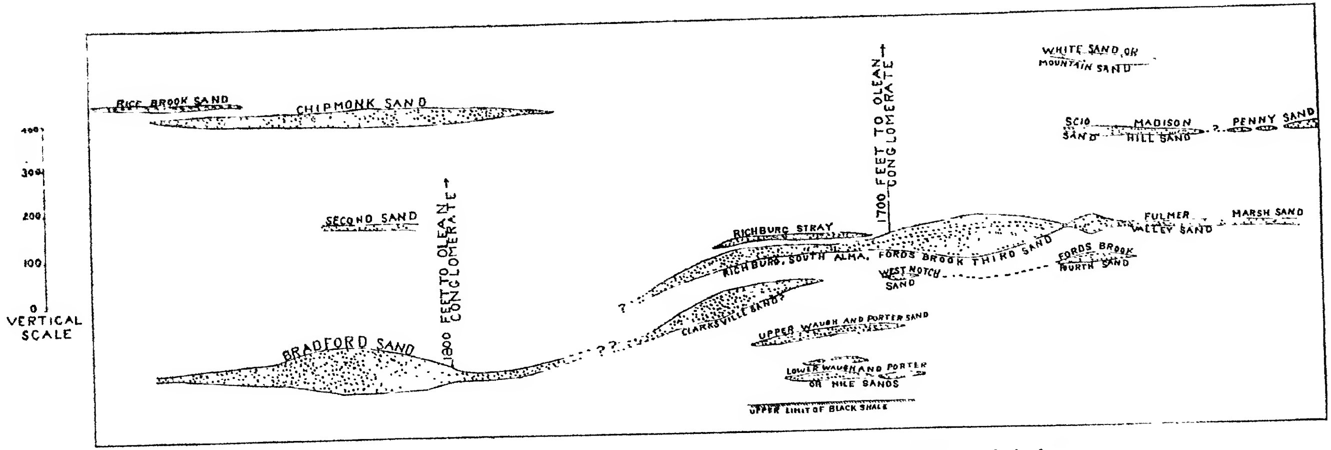

FIG. 3.—Diagram showing the relation of the oil sands of New York state. Vertical scale in feet.

most of the sands. Oil sands from the Richburg and Bradford pools are very similar both in hand specimens and in thin sections.

A petrographic examination of a thin section of a typical producing oil sand from a depth of 980 feet in a well at Richburg, Allegany County,

TABLE II

Character of material	Thickness in Feet	Depth in Feet
1. Clay, sand, and gravel	100	100
2. Dark gray shale	30	130
3. White sandstone and shale	40	170
4. Red shale and sandstone	15	185
5. Chocolate shale	5	190
6. Red sandstone and shale	16	206
7. Chocolate shale and sandstone	4	210
8. Gray sandstone containing water	8	218
9. Gray sandstone	12	230
10. Red sandstone	6	236
11. Gray slate	30	266
12. Gray shale	14	280
13. White shale and sandstone	3	283
14. Gray shale	4	287
15. Gray sandstone	4	291
16. Dark gray sandstone	7	298
17. Gray slate	30	328
18. Light gray shale	20	348
19. Gray slate containing sand shales	21	369
20. Light gray slate	79	448
21. Gray shale containing fragments of fossils	4	452
22. Soft gray slate	31	483
23. Argillaceous sandstone	22	505
24. Gray shale	30	535
25. Gray shale containing fragments of fossils	4	539
26. Red shale	1	540
27. Gray slate	52	592
28. Gray shale containing fossil remains	4	596
29. Gray slate	21	617
30. Gray shale containing fossil remains	1	618
31. Soft gray shale	47	665
32. Gray sandstone	40	705
33. Dark gray shale and slate	80	785
34. Gray slate containing fragments of fossils	61	846
35. Gray sandy shale containing fragments of fossils	9	855
36. Gray shale	120	975
37. Gray sandstone containing oil and salt water	20	995
38. Gray shale	114	1,109
39. Soft gray sandstone, top of oil sand	17	1,126
40. Harder gray sandstone	17	1,143
41. Soft gray sandstone, bottom of oil sand	10	1,153
42. Gray shale and slate	24	1,177

showed an even-grained sandstone, in which the quartz grains occurred as subrounded to angular particles, with an average diameter of 0.15 millimeter. Some feldspar of both the monoclinic and the triclinic varieties

was present. Mica was found in small amounts—both muscovite and biotite. There were also present a few black particles which may represent decomposed hornblende. There was some secondary calcite resulting from the alteration of the silicate minerals. The interstices were partly filled with secondary products, such as quartz and calcite stained brownish probably by the hydrocarbons present in the pores.

A thin section of brownish-gray oil sand from Bradford pool at Knapp Creek was found on examination to be similar to the Richburg thin section, but contained more secondary products of alteration and more secondary silica, which cemented the grains to a considerable extent.

CONTINUITY

On account of their lenticular nature the thicknesses of the sands differ greatly from place to place. In the larger Bradford and Richburg pools, however, fairly constant thickness is maintained throughout considerable areas (Fig. 4). In the more important and larger pools, the reported thickness of the best producing sands ranges from 30 to 60 feet. Thin shale breaks in the oil sands are present in most localities, so that actual thickness of producing oil sand is generally overstated in the well logs. The average thickness of the sands for all the fields would probably not exceed 20 feet. Overlapping of sand lenses at slightly different horizons in the Chemung formation has caused perplexing problems for drillers, and distinctive sand lenses at nearly the same horizon have been equally confusing. In some wells these interrupted sands between the lenses constitute the dry streak of the drillers. The small size of some of the lenses is shown by the fact that a single producing well may be surrounded by dry holes. The Penny sand, one of the higher producing sands, is evidently made up of a series of separate lenses at about the same geological horizon.

POROSITY

The porosity of the sands that have been tested from both the Richburg and the Bradford pools is uniformly low. The range in porosity of six samples from good producing wells was between 12 and 17, figures which may be regarded as fairly representative. Higher porosities have been reported in a few cases, and there are some sands in nearly every well recorded as productive in which the porosity seems to be much lower than the range in porosity given. Variations in porosity of sands in the same well at different depths are not rare and are commonly due to the presence of shaly material or to greater cementation of the sand grains, either of which factors has the effect of lessening the pore space. Even a

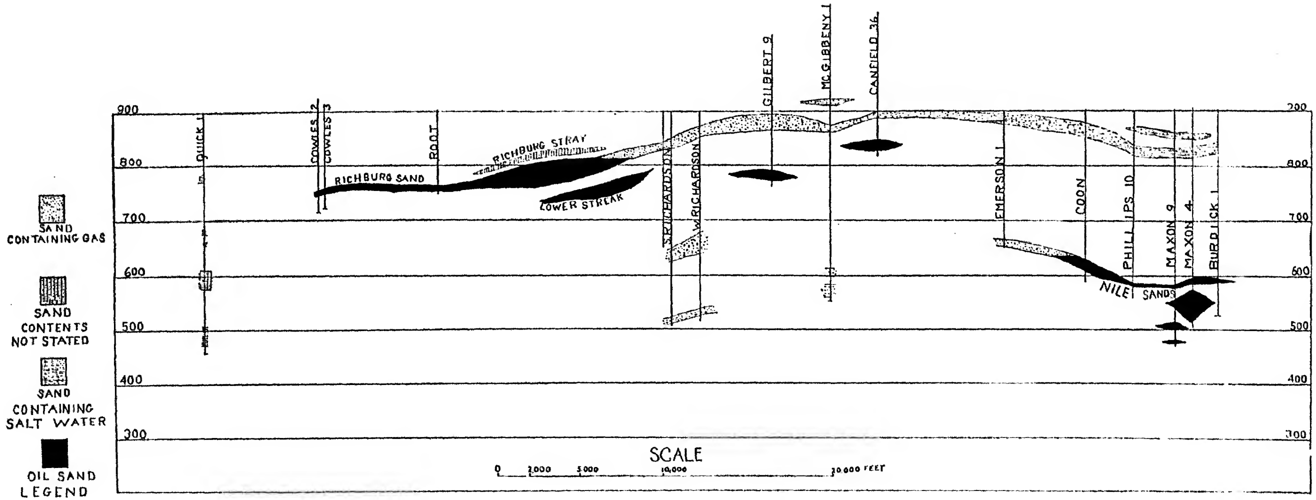

FIG. 4.—Section *A-B* (Fig. 1) through Nile-Richburg pools. Depths shown in feet.

casual examination of certain samples under the microscope shows the presence of shale. In sands free from shale, the quartz grains are very fine and the pore spaces correspondingly small. Small pore space is an important factor in causing the sand to produce oil slowly and in contributing to the long life of the wells.

ORIGIN

The Chemung sediments which include all of the producing oil sands were deposited in comparatively shallow waters of the Appalachian sea. The material laid down was derived from the old lands at the southeast and east. The marine origin of the sediments is shown by the plentiful fossils found in many of the beds of sandstone and shales. The few thin beds of impure limestone which occur among the sandstones and shales are largely composed of organic remains. Marine fossils also characterize the oil sands, and the pearly luster of the brachiopod shells is in striking contrast with the dark color of the oil rock.

Great irregularity in sedimentation is characteristic of most of the Chemung formation. Individual beds of sandstone and shale rarely retain their lithologic character or thickness for any considerable distance, and this lack of persistency of the beds may be readily observed in a single outcrop or quarry face. The irregularities and intergradations of the shales and argillaceous sandstones of the Chemung formation indicate that they originated under conditions which seemed to imply frequent changes of currents modified more or less by heavy tidal flows. Normal deposition of the transported materials appears to have been frequently interrupted, and at times a local shifting and sorting of the sediments resulted in the formation of irregular and cross-bedded sand bodies, some of which appear to have been sand bars. Coastal lagoon conditions would seem to account for some of the peculiar effects of sedimentation observed and at the same time to provide a nearer source of the coarser sands, some of which may be of delta origin.

SOURCE ROCKS

Although the Chemung formation contains plentiful marine fossils, it is not believed that much of the oil is of local origin. The source of the oil is probably the fossiliferous formations directly underlying the Chemung, all of which are composed of or include thick beds of black and dark brown bituminous shales. Altogether these dark shales aggregate many hundreds of feet in thickness and constitute a well-defined black shale series included between the base of the Chemung and the top of the Onondaga limestone. In descending order from the Chemung the dark

shales are found in or comprise the Portage, Genesee, Hamilton, and Marcellus formations.

RELATION OF ACCUMULATION TO STRUCTURE

The oil fields lie just east of the axis of the great Appalachian geosyncline. The axis inclines gently toward the southwest, and the regional dip is in that direction. The local dips are very low and not easily determined, but minor anticlinal and synclinal folds are present. Where these occur and no salt water is present, the oil is found in the synclines. Absence of much salt water from the pools is a noteworthy feature. For the most part the pools are not outlined by salt water, and beyond the oil-producing limit the sand ordinarily pinches out as in structures of the lens type. Where there is a clearly defined dip in the lens structure, only gas is found in the higher part. The presence of salt water in some beds either directly above or below the sands producing oil may be attributed to separate overlapping sand lenses. One or two oil pools are located on anticlines or terraces in sands containing salt water beyond the limits of the producing territory.

MIGRATION

Other than local migration in the few favorable structures found in the oil region, there is little evidence that the oil has migrated any considerable distance in a lateral direction. The irregularity in the character of the Chemung sediments and the lenticular nature of most of the sand bodies are factors unfavorable to lateral migration. Moreover, in small and overlapping but separate lenses, the occurrence of oil and gas, and in some places of salt water, can best be accounted for as having been derived from the great masses of dark Devonian shales that lie below the oil-bearing rocks.

PHYSICAL AND CHEMICAL CHARACTER OF THE OIL

The prevailing color of the oil is dark green, and when held against the sunlight, a golden green. In a few localities the oil is almost black, and on the border of some of the fields a small amount is light yellow. All the oils are of a high grade with a paraffin base. Specific gravity at 10° C. varies from 38° Bé. to 45° Bé., most operators reporting 42° Bé. Oil, amber in color, from some of the wells in the Chipmonk sand, which lies above the Bradford sand in Cattaraugus County, is reported to have a gravity as high as 47° Bé. The oil from the main sand of the Bradford pool of Cattaraugus County is very similar to that of Allegany County. The gravity and viscosity of oils from the pools of Allegany County are shown in Table III.

No analyses of oil showing fractionation by refining without cracking are available, but Table IV shows the products from Allegany County,

TABLE III

GRAVITY AND VISCOSITY OF OILS, ALLEGANY COUNTY

Pool	Gravity, Degrees Bé.	Viscosity (Say.), 70° F.
Richburg	40.4	40
Fords Brook	39.4	40
Scio	43.4	34
Madison Hill	41.2	36

TABLE IV

ANALYSIS OF PETROLEUM, ALLEGANY COUNTY

YEAR 1904

	Percentage
Benzine and gasoline	11.12
Kerosene	44.43
Wax distillate	24.00
Cylinder stocks	16.08
Loss in refining	4.37
Total	100.00

YEAR 1914

Benzine and gasoline	16.50
Kerosene	25.22
Fuel oil	23.35
Light lubricants	14.66
White wax	2.09
Steam cylinder oil	13.86
Loss in refining	4.32
Total	100.00

YEAR 1924

Benzine and gasoline	32.49
Kerosene	6.71
Fuel oil	24.58
Light lubricants	15.95
White wax	1.36
Steam cylinder oil	15.45
Loss in refining	3.46
Total	100.00

New York, petroleum for the years 1904, 1914, and 1924, which may prove of interest.

OIL PRODUCTION

Satisfactory statistics of production of oil are not available previous to 1891, since in earlier years part of the output, mainly from Cattaraugus County, was combined with that of Pennsylvania. Estimates of the early production, however, have been made as follows. Published figures of production for the whole Bradford field of New York and Pennsylvania from 1878 (at which time there were about 250 wells in New York state) to 1885, inclusive, show 120,000,000 barrels. On the basis of the Pennsylvania geological reports, 5 per cent of this amount was credited to New

TABLE V

PRODUCTION OF OIL IN NEW YORK, 1886–90

Year	Barrels
1886	2,151,486
1887	2,075,000
1888	1,985,983
1889	1,896,966
1890	1,740,998
Total	9,850,433

York, thus giving a yield of 6,000,000 barrels for the period. The Allegany County production from the opening of the field in 1880 to the year 1885, inclusive, which covered the flush period in the state, has been published at 18,205,000 barrels. During the flush period, annual production exceeded 5,000,000 barrels. The production from all the New York fields for the period of 1886 to 1890, inclusive, with the exception of the years 1888 and 1890, which were inserted by the writers, is from estimates published in the *Mineral Resources of the United States*. The estimated production is shown in Table V.

Statistics of production after 1890 are based on published figures from reports of pipe-line companies, supplemented by reports from individual producers for small quantities of oil not accounted for in the pipe-line records (Table VI).

By way of explanation of Tables V–VII, it may be mentioned that the annual increase in production beginning with 1919 is not due to expansion of the fields or the finding of new productive sands but rather to the introduction of flooding methods which are now being regularly employed in many sections of the New York fields. In 1916, when 11,200 wells were producing, the average yield per well was only $\frac{1}{5}$ barrel per day. In 1926, with approximately 14,000 wells producing, the average daily production was about $\frac{1}{3}$ barrel per day. The 1928 production is the largest recorded since 1885, when 2,658,011 barrels were produced.

GAS PRODUCTION

No reliable figures for production of natural gas from the oil fields are available. In the early history of the field large quantities of gas were wasted, and present figures of production do not segregate natural gas obtained from the oil fields from that of the adjacent gas districts and

TABLE VI

PRODUCTION OF OIL IN NEW YORK, 1891–1927

Year	Barrels	Year	Barrels
1891	1,585,030	1910	1,073,650
1892	1,273,343	1911	955,314
1893	1,031,391	1912	782,661
1894	942,431	1913	916,873
1895	912,948	1914	933,511
1896	1,205,220	1915	928,540
1897	1,279,155	1916	874,087
1898	1,205,250	1917	879,685
1899	1,320,909	1918	808,843
1900	1,300,925	1919	851,000
1901	1,206,618	1920	906,000
1902	1,119,730	1921	988,000
1903	1,162,978	1922	1,000,000
1904	1,036,179	1923	1,250,000
1905	949,511	1924	1,440,000
1906	1,043,088	1925	1,695,000
1907	1,052,324	1926	1,956,000
1908	1,160,128	1927	2,242,000
1909	1,160,402	1928	2,573,000
		Total	45,001,724

TABLE VII

SUMMARY OF PRODUCTION

	Barrels
New York—Bradford field, 1878–85	6,000,000
Allegany field, 1880–85	18,205,000
All New York fields, 1886–90	9,850,433
All New York fields, 1891–1928	45,001,724
Total	79,057,157

that from the lower geologic formations including the Medina sandstone, which is one of the important sources of natural gas. In the early history of the field many of the wells in the oil districts produced more than 1,000,000 cubic feet of gas per day. At present, most of the producers report that the amount of gas produced is only sufficient for local needs on the lease. Companies having a surplus of natural gas deliver it to natural gas companies. Natural-gas gasoline is extracted from some

of the natural gas before being run into the gas pipe lines. Gasoline content ranges from 2 to 3 gallons per 1,000 feet of gas. The heating value of the gas varies from 1,000 to 1,100 B.T.U.

WATER

The general absence of salt water from the oil fields of New York is a noteworthy feature. As a rule, the pools are not outlined by salt water; and ordinarily, beyond the limits of the productive pools, the sands either pinch out or contain gas. Certain exceptions to the general absence of salt water may be noted. In an upper sand of the Nile pool, mapped as the northern extremity of the Clarksville pool, salt water occurs in a syncline. In the Scio pool, which is the most northerly pool and one with sands at comparatively shallow depths, the oil-producing area is bordered by salt water. In many localities in both the Richburg and the Bradford pools, there is a distinct salt-water sand at various horizons above the main producing oil sands. Such a salt-water sand is recorded in the log of Triangle well No. 1 (Table II).

The only available analyses of water represent wells where flooding methods are employed for increasing oil recovery. In order to show the character of the ground water before entering a flood well, and its contrasting character after it has passed through the oil sand and has been recovered along with oil in the nearest producing well, the analyses shown in Table VIII were made, through the courtesy of the United States Geological Survey.

DRILLING AND PRODUCTION METHODS

Well drilling is carried on with cable tools and the use of steel or wood derricks. In most wells casing is used only to shut off the surface water, and may extend into the well for a distance of 500 feet, although in many wells 200 or 300 feet of casing is sufficient. Most wells are pumped by old methods, including "powers and jacks" and "on beam." In many wells, however, gas engines operate air compressors which distribute power to the pumps at the wells.

The cost of drilling and equipping a well 1,000 feet deep does not exceed $2,500.00, and, as the maintenance cost is small, wells with very low production can be profitably pumped. Nearly all wells are shot with nitroglycerine after drilling is completed.

LIFE AND FUTURE DEVELOPMENT OF THE NEW YORK FIELDS

Both the Cattaraugus and the Allegany county oil fields have been producing for more than forty-seven years. Since 1899, there has been but little development of the new territory, nearly all of the new wells being

drilled in the old pools between other wells. During the long period since these fields have been opened, the limits of the productive areas have been rather well established by border drilling. Although a small expansion of the present producing areas may be expected through the extension of spurs, it is not probable that there will ever be an important increase of productive territory. At the south the fields are limited by the Pennsylvania border, and on the north the Chemung formation containing the oil-bearing series reaches the surface within a distance of 25 miles from the

TABLE VIII

ANALYSES OF GROUND WATER BEFORE AND AFTER USE IN FLOODING

PARTIAL ANALYSES—PARTS PER MILLION

	Sample No.					
	1	2	3	4	5	6
Cl	22	3,210	121	3,320	36	1,388
SO_4	None	1,032	None	215	Trace	448
HCO_3	209	245	34	245	143	152
Ca	24	500	19	373	24	191
Mg	5	64	10	64	10	21
Na (diff.)	58	1,966	51	1,798	31	910
Sp. G. at 27° C.	....	1.0038	....	1.0015	....	1.0004

Sample No. 1.—Ground water used for flooding on the Rockview lease, Four-mile district, Cattaraugus County. Occurs above depth of 400 feet, with top standing at about 30 feet. Sample pumped from a depth of 200 feet, in Well No. 11.

Sample No. 2.—Water pumped with oil from Rockview No. 25, located 178 feet from No. 11, in which sample No. 1 was taken. No. 25 was producing ½ barrel of oil and 5 barrels of water per day. Sample taken from tank.

Sample No. 3.—Ground water used for flooding on Reed farm, Richburg, Allegany County. Taken from Well No. 03, Lot 40. Comes into well between the bottom of the conductor at a depth of 122 feet and the top of the casing at a depth of 293 feet.

Sample No. 4.—Water pumped with oil from Reed No. 19, Lot 40, located 149 feet from No. 03. Production at time of sampling, 1½ barrels of oil and 9 barrels of water per day.

Sample No. 5.—Ground water being pumped through pressure plant from well on Thornton lease, Lot 17, Alma, near Allentown in Allegany County. Pump intake at a depth of 200 feet.

Sample No. 6.—From producing well, Thornton No. 12, Lot 17, Alma, about 175 feet from groundwater well.

pools already developed. Neither east nor west of the present fields has deep drilling resulted in the finding of any important oil supplies. The discovery of a few small outlying pools is the most that can be expected. In the territory north of the present producing fields, many wells have been drilled, and these have yielded only gas. It is therefore unlikely that the oil fields can ever be much extended in this direction.

The only hope of finding additional supplies of oil of any importance in the present fields seems to be by deeper drilling. No deep tests have been made in the oil fields; but in the counties on the north, approximately 1,500 gas wells have been drilled, some of which went as low as the Tren-

ton limestone, and two or three wells are recorded as having reached the pre-Cambrian. In only a few of these wells has there been a showing of oil, although two wells actually had oil production. The deeper formations underlying the oil fields may, however, be regarded as untested.[1]

One of the interesting features of the New York wells is their longevity. As previously mentioned, Triangle No. 1 has been producing during a period of more than forty-eight years. Other wells are known that have produced for more than forty years, and wells that have produced for more than thirty years are common. Of the 14,000 producing wells in the state, possibly more than half the number have produced for a period exceeding twenty years. The fineness of the sand, the low porosity, and the low but ever-present gas pressure are the important factors contributing to the long life of the wells, while the low cost of upkeep and the high grade of oil produced make the pumping of the wells profitable even after daily production is but a small fraction of a barrel.

The future life and production of the oil fields are dependent on several factors that do not apply to fields using the ordinary or natural methods of production. Before the introduction of flooding methods, when the annual production in the state had decreased to approximately 750,000 barrels, it seemed that the end of life of the fields was close at hand. Under favorable conditions, however, the results of flooding give additional recoveries ranging from 2,000 to more than 5,000 barrels per acre. A conservative estimate of future production is 85,000,000 barrels as against past production of 79,000,000. Much larger estimates have been made, but these have been based on the assumption that favorable conditions for flooding will be found to exist in practically all the areas where flooding has not yet been tried. Should favorable conditions for flooding be found in all of the important pools, future production may exceed 300,000,000 barrels. Because the floods travel slowly—from 50 to 200 feet per year—it would seem that even with an intensive program of flooding, the fields will continue to produce for a period of 50 years or more. In addition to flooding methods, a more extended use of air, natural gas, and other new and improved methods for obtaining additional quantities of oil, together with cost of production, will be important factors in determining the length of time the fields will be productive.

[1] Since the foregoing was written, a test well 2 miles north of Richburg, Allegany County, at a depth of 4,010 feet at the horizon of the Tully limestone, on Sept. 15, 1928, encountered a flow of gas ranging in amount from 4,500,000 to 5,000,000 cubic feet daily. The well also produces about 25 barrels of high-gravity oil daily. Another deep well is now being drilled in the Richburg field; and others, some of which may be drilled to the Trenton limestone, will be commenced in the near future. (C.A.H.)

HEWITT OIL FIELD, CARTER COUNTY, OKLAHOMA[1]

GEORGE E. BURTON[2]
Ardmore, Oklahoma

ABSTRACT

The Hewitt field is the second largest field in southern Oklahoma. It is an example of an anticline overlying a buried hill. The rocks at the surface are Permian Red-beds. The oil is found in sands of Pennsylvanian age.

The discovery well in the Hewitt field was located on the basis of surface geology. Later development, however, proved the subsurface "high" on the top of the first Hewitt sand to be considerably north of the well.

The maximum production was reached in the month of September, 1921, when the daily average was 43,902 barrels. At the end of 1927 the field had produced 19,786 barrels per acre. It is estimated that at the end of 1941 the total yield per acre will be 27,301 barrels.

LOCATION

The Hewitt oil field covers approximately 4.8 square miles in Secs. 9, 10, 15, 16, 21, 22, 23, 27, and 28, T. 4 S., R. 2 W., Carter County, Oklahoma, 15 miles west and 2 miles north of Ardmore. It is 2 miles east of the eastern edge of the Healdton oil field, 3 miles south of the Wheeler oil field, and 6 miles south of the Graham oil field. The "Southeast extension" of the Hewitt field is near the northwest corner of Section 36, 1 mile southeast of the main field.

ACKNOWLEDGMENTS

Several earlier papers[3] have been published on the Hewitt field. To W. E. Hubbard, who was in charge of the geological work for the Humble Oil and Refining Company during the development of the field, the writer is indebted for a subsurface structure-contour map of the field, which is reproduced as Figure 2 with slight revisions. He is also indebted for assistance to Sidney Powers, T. K. Harnsberger, D. K. Greger, Fannie

[1] Presented by title before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, November 22, 1927.

[2] Consulting geologist, 419 Simpson Building.

[3] T. E. Swigart and F. X. Schwarzenbek, "Petroleum Engineering in the Hewitt Oil Field, Oklahoma," *U. S. Bur. Mines* and *Ardmore Chamber of Commerce* (Ardmore, 1921); Louis Roark, "The Hewitt Oil Field, Carter County, Oklahoma," *Indiana Acad. Sci., Proc. 1921*, pp. 211–20 (1922); C. W. Tomlinson, "Oil and Gas Geology of Carter County, Oklahoma," *Oklahoma Geol. Survey Bull. 40-Z* (1928), chapter by George E. Burton on "Hewitt," pp. 42–48.

Carter Edson, B. H. Harlton, Robert Roth, and E. D. Luman. C. J. Cunningham collected and assembled the material, and Charis Miller did the drafting.

HISTORY

This field was discovered on June 5, 1919, by The Texas Company's A. E. Denny No. 1, NE. ¼, NW. ¼, NW. ¼, NW. ¼ of Sec. 27, which found an oil sand from a depth of 2,100–2,134 feet. The initial production was 410 barrels. This well proved to be one location from the southwestern corner of the field.

William J. Millard discovered the Hewitt anticline for The Texas Company in October, 1916. The original dip-and-strike map is reproduced in Figure 1. His interpretation of the geology, as judged from the map, was that the Healdton field, then ending in Sec. 13, T. 4 S., R. 3 W., would extend across the Hewitt area as far east as Section 26, with high points in Sections 19 and 21. Before the Hewitt discovery well was commenced, it was found that Healdton was defined on the east by thinning of the producing sands. The exact location of the discovery well was selected because of lease conditions.

Hewitt was developed rapidly in the shallow-sand zone of the first producer, and on September 30, 1920, there were 235 wells producing 31,020 barrels a day. After the deeper pay zones were discovered in November, 1920, a new period of excitement led to an intensive drilling campaign in 1921. A maximum production was reached in September of that year, when 570 wells produced 43,902 barrels a day during the month. On December 31, 1927, there were 806 wells producing 9,075 barrels of oil daily.

In June, 1922, Baker and Strawn in their Dillard No. 8-B, 1,610 feet east and 290 feet south of the northwest corner of Sec. 22, T. 4 S., R. 2 W., discovered deeper oil in secondary limestone from 2,863 feet to 2,878 feet. The initial production of the well was 450 barrels. Approximately 24 wells were drilled in the vicinity of the Baker and Strawn discovery in search of this deep production. The Carter Oil Company's Noble No. 33, SW. ¼, NE. ¼, NE. ¼, Sec. 21, T. 4 S., R. 2 W., was the most sensational well, making 14,000 barrels initial production from "pay" at a depth of 2,941–43 feet. On account of the quick decline of this limestone production, the search for this oil was soon abandoned. It has been only a small factor in the production of the field.

GENERAL GEOLOGY

Hewitt is in the regional syncline of Permian Red-beds. It is 12 miles southwest of the Arbuckle Mountains, where the unconformable contact

of these rocks and the underlying Pontotoc series of uppermost Pennsylvanian age and the older Pennsylvanian rocks may be observed. The thickness of Red-beds is 200 feet in the center of the field and approximately 1,300 feet on the edges.[1] An isopach map of the Red-beds was

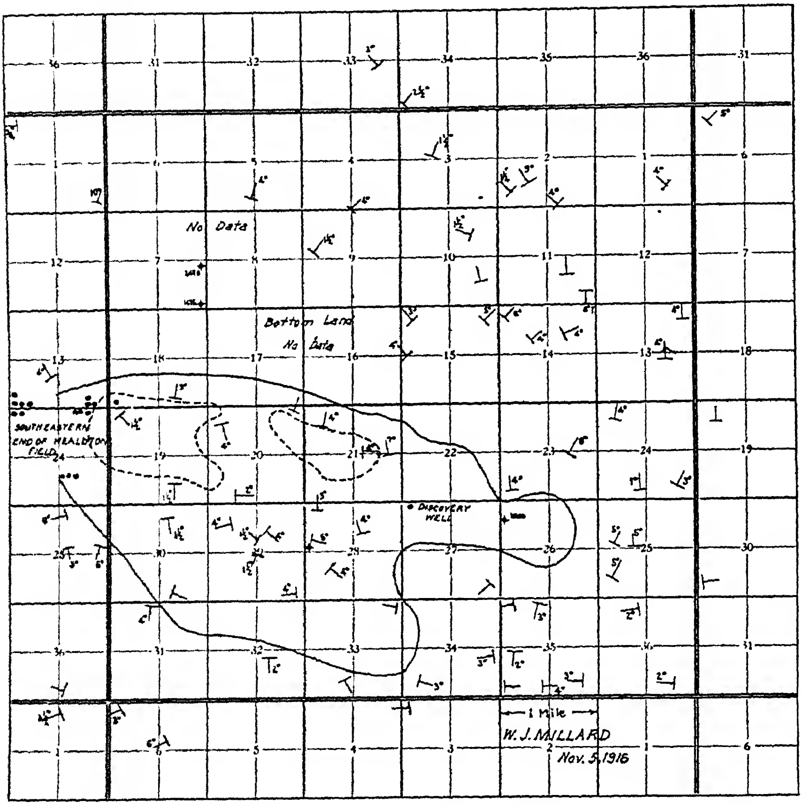

FIG. 1.—Dip and strike map of surface rocks at Hewitt oil field, T. 4 S., R. 2 W., Carter County, Oklahoma.

published by Hubbard.[2] Regional structure in the Permian can be recognized from surface outcrops, as shown in the Geological Map of Oklahoma,[3] and the anticlinal folds overlie anticlines in the Pennsylvanian strata.

[1] G. E. Burton, "Relation of the Base of the Red-Beds to the Oil Pools in a Portion of Southern Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 5, No. 2 (1921), pp. 173–77.

[2] T. E. Swigart and F. X. Schwarzenbek, *op. cit.*, Fig. 4.

[3] *U. S. Geol. Survey* (1926).

However, the obscurity of detailed relation between structure at the surface, as shown in Figure 1, and the thickness of the Red-beds, as revealed by drilling, and also the Pennsylvanian structure, indicate that in Permian time the Pennsylvanian folds were probably hills over which the lower Permian beds did not extend.

Pennsylvanian beds underlie the Red-beds. The highest is the Pontotoc series,[1] which ranges from 400 feet in thickness on the anticline to 1,100 feet on the edges of the field. It consists of approximately 65 per cent shale, 15 per cent sand, 15 per cent sandy shale, and 5 per cent lime. Most of the sands contain water, but some gas was found by the early wells.

A zone of blue shale with a uniform thickness of 300 feet extends throughout the field. It is correlated with the Deese formation of the upper Glenn group.

The main oil-bearing zone is 700 feet thick and belongs to the Deese formation. The oil sands of the Healdton field are probably also in this zone.

Unconformably beneath the oil sands deep wells have penetrated Caney shale or Woodford chert (Chattanooga shale). Older rocks have not been found in available cuttings. The highest buried peaks of these rocks are approximately 2,800 feet below the surface. Very few cuttings from these wells are available; therefore, the structure of the pre-Pennsylvanian rocks cannot be deciphered.

PRODUCING HORIZONS

Shallow gas sand.[2]—During the development of the field a gas sand with an average thickness of 20 feet was found in the NE. ¼ of Section 22 at a depth ranging from 250 to 400 feet, with an average thickness of 20 feet. It is approximately 1,000 feet above the Hewitt oil sand. This sand is in the top of the Pontotoc series and is cut off on the north and east by truncation and overlap of the Red-beds. On the south and southwest it carries water. Gas was not found in commercial quantities, and oil in a few wells was heavier than that in the deeper sands.

The 600-foot gas sand.—Another sand in the Pontotoc series, at a depth of 600 feet in a sandy zone 90 feet thick, yielded gas wells and a few oil

[1] R. A. Birk, "The Extension of a Portion of the Pontotoc Series around the Western End of the Arbuckle Mountains," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 9, No. 6 (September, 1925), pp. 983–89.

[2] Descriptions of these sands are abstracted from T. E. Swigart and F. X. Schwarzenbek, *op. cit.*

wells in the N. ½ of Section 22. The sand was not found in Section 15, due to pinching-out.

Stray sands.—Several sands were noticed above the Hewitt sand, one being 280 feet and another 70 feet above this sand. They are in the Deese formation.

Hewitt sand series.—The first Hewitt sand was the principal producing horizon until deeper sands were discovered. It is continuous and is found at a depth of 1,200 feet on the apex of the anticline in the center of the N. ½ of Section 22. On the north line of Section 27 it is 2,000 feet, or more, below the surface, indicating a dip of 1,200 feet to the mile, except where interrupted by faults. Oil is produced from this sand on the southwest flank of the anticline 1,000 feet, or more, down the dip. The thickness of the sand ranges from 30 to 60 feet.

The Hewitt sand series, as defined by the Bureau of Mines, is 700 feet in thickness and contains seven recognized oil sands without intervening water sands. The distribution, thickness and productivity of the sands below the first sand are variable. Rotary drilling methods and production tests of several sands at once add to the difficulty of distinguishing individual sands. The depths of these sands below the top of the first Hewitt sand are as follows: second, 70–100 feet; third, 170–200 feet; fourth, 300 feet; fifth, 400 feet; sixth, 640 feet (depth below the surface approximately 2,300–2,350 feet near the center of Section 22); seventh, 700 feet.

Gusher production was found in the erosional zone between the sands of the Deese formation and the pre-Pennsylvanian rocks. Much of this production came from a thick porous limestone at depths ranging from a few feet to 170 feet below the top. The depth of production in this zone ranges from 2,800 feet to 3,075 feet with initial production ranging from 20 to 14,000 barrels a day. Showings of oil are reported as deep as 3,642 feet, but it is not known whether they are in this erosional zone or in the underlying rocks.

STRUCTURE

Hewitt is an anticline with a north-south axis extending through Sections 15 and 22, as shown in Figure 1. The anticline in the Red-beds has dips ranging from 30 to 40 feet to the mile. It is more steeply folded in the underlying Pontotoc series and still more steeply folded in the upper Glenn group, with dips of 1,200 feet to the mile. The anticline overlies a rim of these truncated and older rocks dipping northward, the Hewitt Hills, comparable with the buried Healdton Hills under the Healdton oil field, but not as deeply truncated as the latter hills. This older ridge

resembles in form a hogback and at Healdton is bounded on the south and southwest by a fault or by an erosional scarp. The entire feature has been referred to by Sidney Powers[1] as the north rim of the buried southeastern extension of the Wichita Mountain system (Fig. 2). It is separated from the Arbuckle Mountains by a deep synclinal trough of Pennsylvanian and Permian beds which have been folded into closely compressed, elongate anticlines and synclines. The Wheeler, Graham, Fox, Sholem Alechem, Tatums, and other oil fields have been developed on these anticlines. South of the Healdton Hills, west of the Criner Hills, and north of the Hambro oil field, no folds have been proved to exist.

GEOLOGIC HISTORY

The Arbuckle-Wichita Mountains section of Paleozoic rocks was deposited in the Red River area. The recent discovery of Viola limestone in north-central Texas by M. G. Cheney[2] indicated that the complete Paleozoic section, formerly thought never to have been deposited in that part of Texas, was probably present at one time. Uplift of the mountains in Oklahoma and of the Red River arch along Red River took place after the deposition of the Springer formation (Pennsylvanian Caney shale) and during early Glenn time. The upper Glenn (Deese formation) transgresses the folded and beveled edges of the buried part of the Criner Hills and contains conglomerate derived from Ordovician limestones. Pre-upper Glenn Pennsylvanian strata have not been found by drilling southwest of the Criner and Healdton hills.

A second uplift is proved by the unconformity between the Pontotoc series and underlying Glenn formation, as observed at Hewitt and elsewhere.

A third uplift followed deposition of the Permian Red-beds, but folding of these beds was such as to show regional movements; and the local structure which can be mapped in them at the surface and by core drills is in many places merely cross-bedding, or else it represents structure which extends through the Red-beds only or through them and the underlying Pontotoc series only.

Trinity sand of lower Cretaceous age formerly covered the Hewitt area but has been removed by erosion. Post-Cretaceous diastrophism has

[1] Sidney Powers, "Age of the Folding of the Oklahoma Mountains—the Wichita, Arbuckle, Ouachita Mountains of Oklahoma, and Llano Burnet and Marathon Uplifts of Texas," *Bulletin Geol. Soc. Amer.*, Vol. 39 (1929).

[2] "Pre-Mississippian Production in Texas," *Oil and Gas Jour.* (April 12, 1928), p. 31.

consisted largely of warping. There have been readjustments of drainage to structure, but they are very obscure.

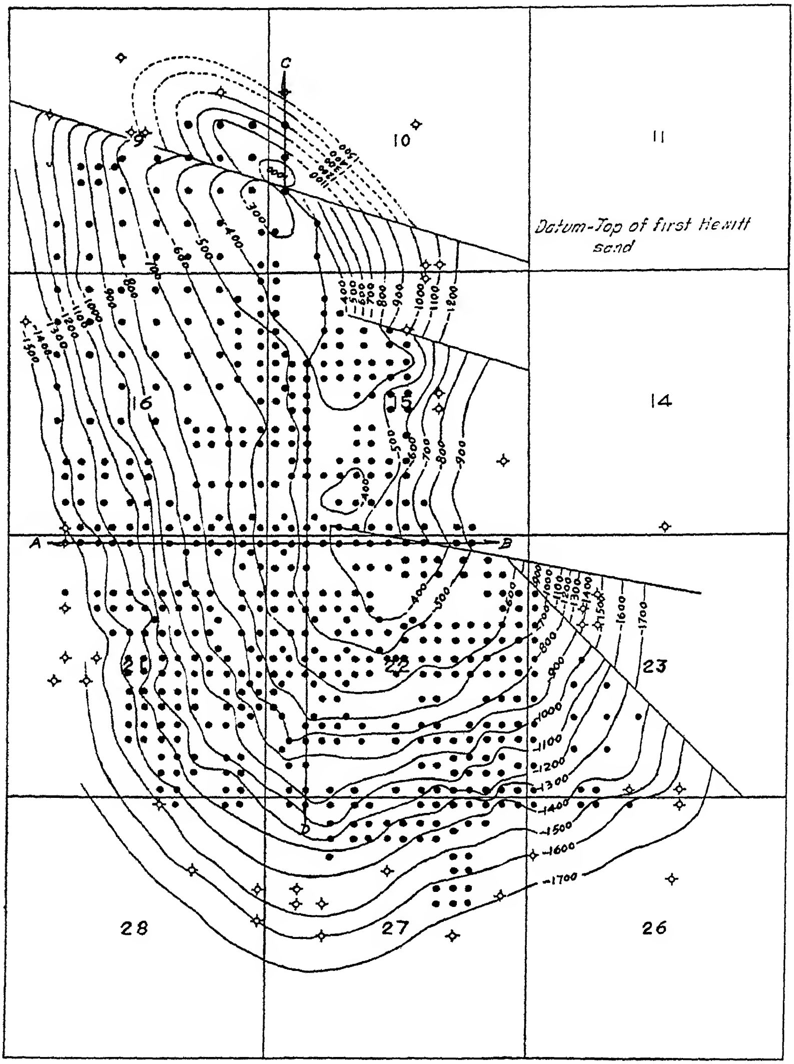

FIG. 2.—Subsurface structure of Hewitt field, T. 4 S., R. 2 W., Carter County, Oklahoma, modified from map by W. E. Hubbard of the Humble Oil and Refining Company, as published in "Oil and Gas Geology of Carter County, Oklahoma," *Oklahoma Geol. Survey Bull. 40-Z* (1928), p. 45. Width of area mapped, 3 miles.

SOUTHEAST EXTENSION OF HEWITT OIL FIELD

Approximately 1 mile southeast of the southeastern end of the Hewitt oil field there is a productive area generally known as the "Southeast extension." The production comes from the same section of rocks as does

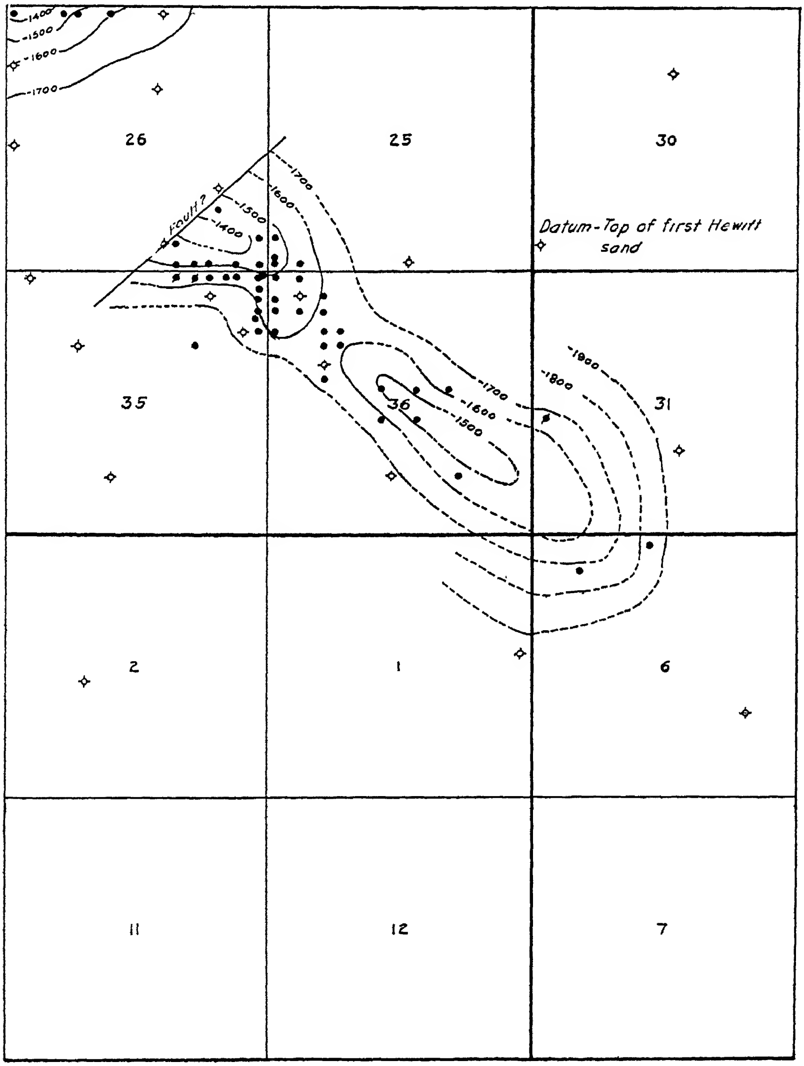

FIG. 3.—Subsurface structure of Southeast extension, Hewitt field, T. 4–5 S., R. 1–2 W., Carter County, Oklahoma. Width of area mapped, 3 miles.

the production in the main Hewitt pool, except that rocks older than Pennsylvanian have not been found. The writer's idea of structural conditions is shown in Figure 3. The contours are drawn on top of the first Hewitt sand. The production is associated with a rather long, narrow, northwest-southeast-trending fold. The fold seems to be cut off abruptly at the northwest end of the pool by a northeast-southwest trending fault.

PRODUCTION

Table I shows the production of the Hewitt field and the Southeast extension up to the end of 1927, as well as the estimated future production. Figure 4 shows the production curve. Up to the end of 1927, Hewitt and the Southeast extension has produced 60,349, 876 barrels of oil. By carrying the production curve to that point where the average production per

TABLE I

YEARLY PRODUCTION, IN BARRELS, HEWITT FIELD

Year	Wells	Producing Days	Average per Well per Day	Yearly Production	Cumulative Production
1919	7	521	340.0	177,876	177,876
1920	396	57,049	130.0	7,426,000	7,603,876
1921	605	201,917	64.5	13,095,000	20,698,876
1922	692	240,756	44.4	10,690,000	31,388,876
1923	733	263,586	33.0	8,695,000	40,083,876
1924	796	285,882	24.2	6,905,000	46,988,876
1925	809	296,480	18.0	5,315,000	52,303,876
1926	793	291,509	14.4	4,202,000	56,505,876
1927	806	292,311	13.1	3,844,000	60,349,876
1928	808	295,728	11.4	3,380,000	63,729,876
1929	808	294,920	9.8	2,880,000	66,609,876
1931 (est.)	808	589,840	7.6	4,500,000	71,109,876
1933 (est.)	808	590,648	5.9	3,500,000	74,609,876
1935 (est.)	808	589,840	4.7	2,760,000	77,369,876
1937 (est.)	808	590,648	3.9	2,300,000	79,669,876
1939 (est.)	808	589,840	3.3	1,950,000	81,619,876
1941 (est.)	808	590,648	2.8	1,650,000	83,269,876

well per day is 2.8 barrels, it is estimated that the area, with present methods of production, will produce an additional 22,920,000 barrels. There are 3,050 producing acres in this area. Up to the end of 1927, the yield per acre was 19,786 barrels. At the present rate of decline, at the end of the year 1941 an additional per-acre yield of 7,515 barrels will be produced, making the total yield per acre, 27,301 barrels. The actual and the estimated productions are shown in Table I.

The Hewitt pool came in and produced a large part of the flush production when the price of oil was comparatively high; consequently, it has made considerable money for the operators.

CROMWELL FIELD, SEMINOLE AND OKFUSKEE COUNTIES, OKLAHOMA[1]

A. A. LANGWORTHY[2]
Tulsa, Oklahoma

ABSTRACT

The Cromwell field occurs in a belt or zone of *en échelon* faulting as expressed in the surface sediments which are composed of sandstone and shale belonging to the Francis formation of Pennsylvanian age. The surface irregularities and faulting are believed to be a reflection of subsurface folding, and possibly subsurface faulting. The Cromwell sand (Lyons sand) of Pennsylvanian age has been the source of practically all of the oil. The "Wilcox" sand, which is one of the sand members of the Simpson formation of Ordovician age, has produced a small amount of oil. The Cromwell and the "Wilcox" sands are found at average depths of 3,400 feet and 4,150 feet, respectively. The migration of oil up the dip from the west has been intercepted by two subsurface structural features, namely, a fault with more than 214 feet of displacement and a dome with 70 feet of closure. Production bears a close relation to these structural features, and there would have been a closer relation had local sand conditions not interfered.

LOCATION

The Cromwell field is located in T. 10 and 11 N., R. 8 E., Seminole and Okfuskee counties, Oklahoma. It is 12 miles northeast of the Seminole City field of the Seminole district and 15 miles north of the Wewoka field.

HISTORY

The discovery well of the Cromwell field was drilled by the Cosden Oil and Gas Company (now the Mid-Continent Petroleum Corporation) on the J. Willis farm, and was located in the southeast corner of the NW. ¼ of Sec. 15, T. 10 N., R. 8 E. (Fig. 2). On November 13, 1922, this well was completed as a gas well, making 30,000,000 cubic feet daily and a spray of oil. The producing horizon, later designated as Cromwell sand, was encountered at a depth of 3,456–66 feet. August 3, 1923, Jarvis and Holm, drilling in the northeast corner of the SE. ¼ of Sec. 21, T. 10 N., R. 8 E., drilled into sand at 3,482 feet and had 3,200 feet of high-grade oil in the hole. They were unable to complete their well for some time, owing to the lack of tankage and pipe-line connections. The Cromwell Oil and Gas Company completed the first oil well of the field, as their P.

[1] Manuscript received by the editor, October 27, 1928.

[2] The Pure Oil Company.

Bruner No. 1 began flowing in October, 1923, and on November 21 was flowing 330 barrels, natural. This well, completed in sand at 3,467–3,501 feet, is located in the northwest corner of the NE. $\frac{1}{4}$, SW. $\frac{1}{4}$ of Sec. 15, T. 10 N., R. 8 E. (Fig. 2). Correlation of the producing horizons encountered in these three wells proved that the sands were the same, and the name "Cromwell sand" was designated for this pay sand in honor of J. I. Cromwell, president of the Cromwell Oil and Gas Company. The Cromwell sand is correlated with the Lyons sand of the Lyons pool in Sec. 25, T. 11 N., R. 11 E., and with the Papoose sand of the Papoose pool in T. 9 N., R. 9 E.

Development extended rapidly toward the north, west, and south, and in August, 1924, reached its peak, which was slightly in excess of 62,000 barrels daily from 84 wells (Fig. 7). In August, 1928, 387 wells were producing 9,300 barrels daily. To September 1, 1928, the field had produced 35,066,000 barrels. The gravity of the oil varies from 38° to 40° Bé. In nearly all wells the oil was preceded and accompanied by large volumes of rich gas which had an average gasoline content of 4.2 gallons per 1,000 cubic feet of gas. In some wells the gasoline content amounted to as much as 8.84 gallons per 1,000 cubic feet of gas. During the course of drilling, other possible oil horizons were tested. Several wells located in Sec. 33, T. 11 N., R. 8 E. produced from 25 to 150 barrels, from a sand near the base of the Calvin sandstone, ranging from 1,850 to 1,900 feet in depth. The Booch sand, which is encountered from 3,000 to 3,200 feet in Secs. 15 and 22, T. 10 N., R. 8 E. (see Figure 1, between 3,030 and 3,060 feet), had excellent showings of oil and gas, a few wells having produced several million cubic feet of gas a day. Some of the wells in the field produced small quantities of oil from the Gilcrease series (see Figure 1, between 3,190 and 3,230 feet). The largest of these wells was the Independent Oil and Gas Company's H. Harjo No. 1, in the southeast corner of the NW. $\frac{1}{4}$, NE. $\frac{1}{4}$ of Sec. 21, T. 10 N., R. 8 E., which produced 300 barrels per day from a sand at a depth of 3,376–96 feet. Commercial production of oil below the Cromwell sand was found in the "Wilcox" sand member of the Simpson formation, ranging from 4,000 to 4,200 feet on the dome in Sec. 33, T. 11 N., R. 8 E. (Figs. 1 and 3). The Continental Oil Company's Pierce No. 4, in the northwest corner of the SW. $\frac{1}{4}$, SE. $\frac{1}{4}$ of Sec. 33, T. 11 N., R. 8 E., produced 1,440 barrels a day after being shot, and was the best producer in this horizon. The gravity of oil from the "Wilcox" sand is 37.1° Bé. The dome in Sec. 33, T. 11 N., R. 8 E, is the only locality in which there is commercial production of oil from the "Wilcox" sand, all other "Wilcox" sand tests in the field being dry.

Only two papers referring to the Cromwell field have been written, one by C. O. Rison and J. R. Bunn,[1] the other by O. R. Grawe.[2]

ACKNOWLEDGMENTS

The suggestions of Sidney Powers, of the Amerada Petroleum Corporation, and Lyndon L. Foley, of the Mid-Kansas Oil and Gas Company, have been helpful in the preparation of this paper and the writer wishes to express his appreciation of their assistance.

STRATIGRAPHY

The stratigraphy of the Cromwell field is illustrated in Figure 1. Cuttings were collected from many wells in the field as they were drilled. In one particular case a standard cable-tool well near the center of the field was selected and cuttings were saved from each five feet of hole drilled from the surface of the ground to the total depth of the well. The stratigraphic column shown in Figure 1 is the result of intensive paleontological study of all of these cuttings by Horace N. Coryell, paleontologist of Columbia University, and Ira H. Cram, paleontologist of The Pure Oil Company.

SURFACE GEOLOGY

REGIONAL LOCATION

The surface rocks of Seminole and Okfuskee counties dip normally toward the west or northwest, interrupted by irregularities, the most prominent of which are three belts or zones of *en échelon* faulting. These fault zones, ranging from 30 to 100 miles in length, trend N. 6°–12° E., and are from 10 to 12 miles apart. The individual faults, ranging from ½ mile to 3 miles in length, are of the normal type, and their strike is N. 20°–45° W. The western zone of faulting includes the Little River, Bowlegs, Seminole City, Searight, Paden, Depew, and West Bristow fields. The Wetumka and Yeager fields are on the eastern zone of faulting. Between these two zones is a third zone of faulting on which the Cromwell field is located. Within this zone are also the Wewoka and East Bristow fields.

SURFACE STRUCTURE

The surface-structure contour map of the Cromwell field (Fig. 2) is the result of plane-table mapping on sandstone outcrops belonging to the

[1] "Petroleum Engineering in the Cromwell Oil Field," *U. S. Bur. of Mines and Office of Indian Affairs* (December 1, 1924), 38 pp.

[2] "The Stratigraphy and Structure of the Cromwell Field, Oklahoma," manuscript read before the Amer. Assoc. Petrol. Geol. at the San Francisco meeting, March, 1928. Abstract published in program.

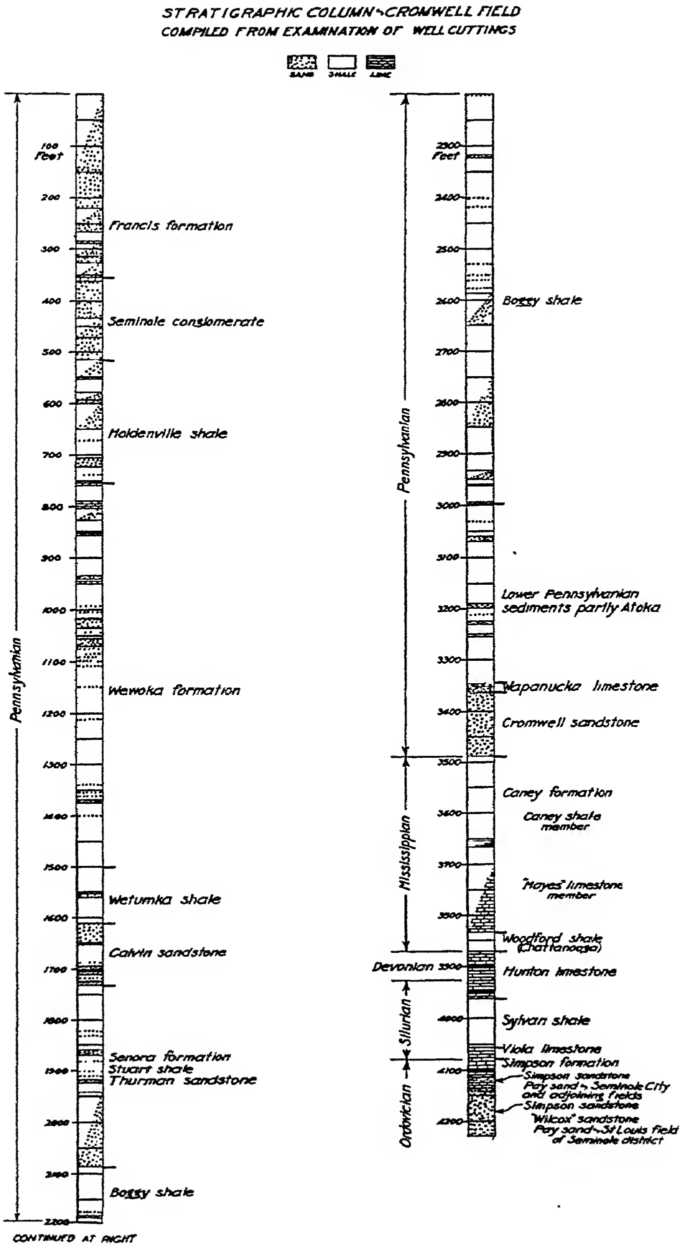

FIG. 1.—Stratigraphic column, Cromwell field.

Francis formation. The contours are above sea-level, and the interval is 10 feet. Where control was positive, the contours are shown as solid lines. In many places the sandstone had slumped, weathered, or entirely disappeared, and correlations became so difficult and questionable the writer thought it advisable to dash the contours.

A zone of *en échelon* faulting interferes with the normal dip of the surface rocks, which averages 80 feet per mile toward the northwest. The throw of the individual faults ranges from a few feet to 70 feet, and the downthrown side may be either on the east or on the west. Only a few slickensided surfaces of the sandstone were observed. Veins of silica or calcite are present in the sandstone bordering some of the faults.

> Such veining is indicative of deep fissuring, which is generally accompanied by some displacement, although the displacement may be very small. If the cementation and formation of the veins were a purely surface phenomenon, one might expect the joint cracks in the rocks to show the same cementation. The fact that these fissures contain minerals not present in the joint cracks of the surface rocks is suggestive that the cementing material may have come from a deep-seated source, the solutions possibly rising along fissures that very likely were formed by stresses which produced actual displacement or faulting.[1]

Veins were detected where they seemed to indicate fracturing of the surface rocks, and no displacement could be observed. As the sandstone outcrops were all similar, and in many places poor, the throw of the faults necessarily had to be determined by tracing the outcrops around the ends of each fault. Various noses and terraces in connection with these faults form the surface structural features of this field.

SUBSURFACE GEOLOGY

The subsurface structure of the Cromwell field is shown in Figure 3. The contours are drawn on the top of the Cromwell sand below sea-level, and the interval is 10 feet. The two main structural features are readily observed. The large fault with more than 214 feet of downthrow toward the east is equivalent to the same amount of east dip or reversal, and forms the closure of the south part of the field. The main structural feature of the north part of the field is the dome in Sec. 33, T. 11 N., R. 8 E., which has 70 feet of closure. To illustrate the large fault and other conditions found in the Cromwell sand, a west-east cross section (Fig. 4) was drawn along line *B-B* of Figure 3. This gives an idea of the thickness of the sand, the amount of sand occupied by gas, and the amount of sand

[1] Personal communications from Philip S. Smith, acting director, U. S. Geol. Survey, and K. C. Heald, November 12, 1922, and A. E. Fath, November 3, 1928.

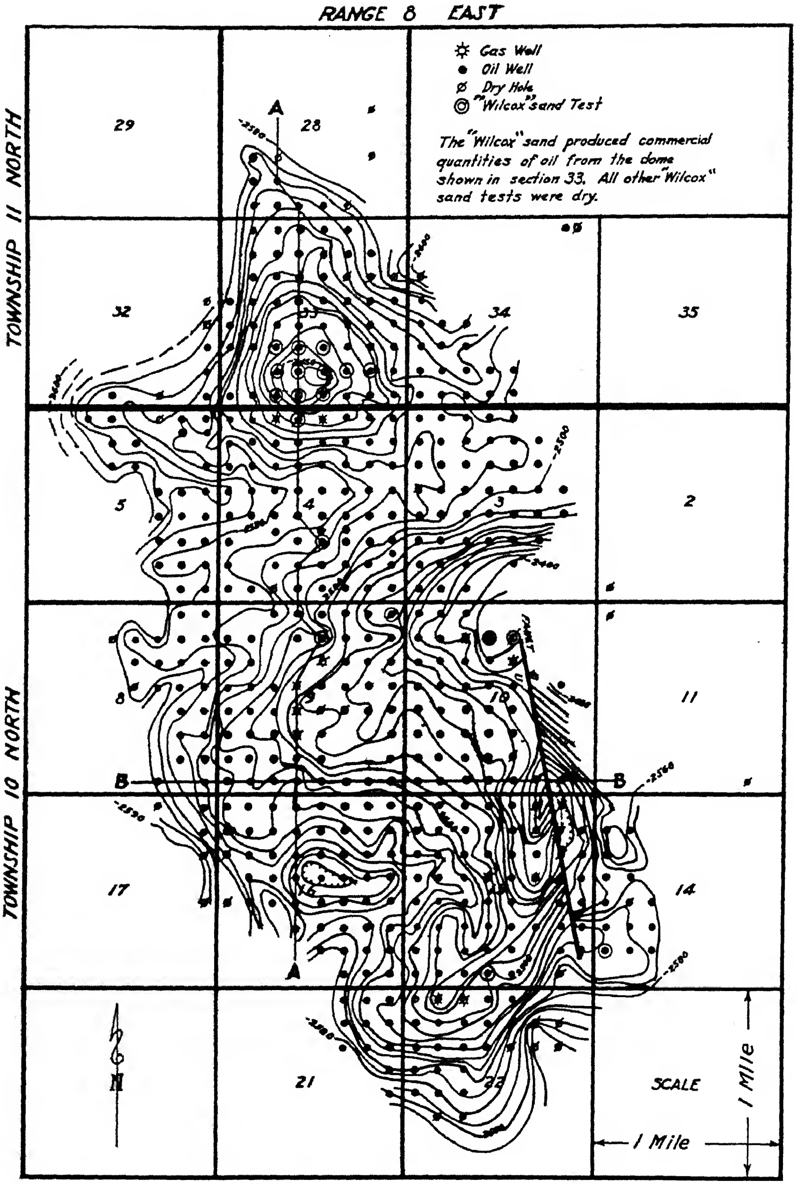

FIG. 3.—Subsurface structure of Cromwell field, contoured on top of Cromwell sand below sea-level. Contour interval, 10 feet. Twin wells are not shown.

considered oil "pay." The gradual rise of the top of the Cromwell sand and the increase in thickness eastward is observed, and finally the fault is encountered. Since all of the producing wells made considerable gas, the logging of the formations is rather questionable in some wells where it was impossible to get cuttings, the gas having blown the cuttings out of the hole.

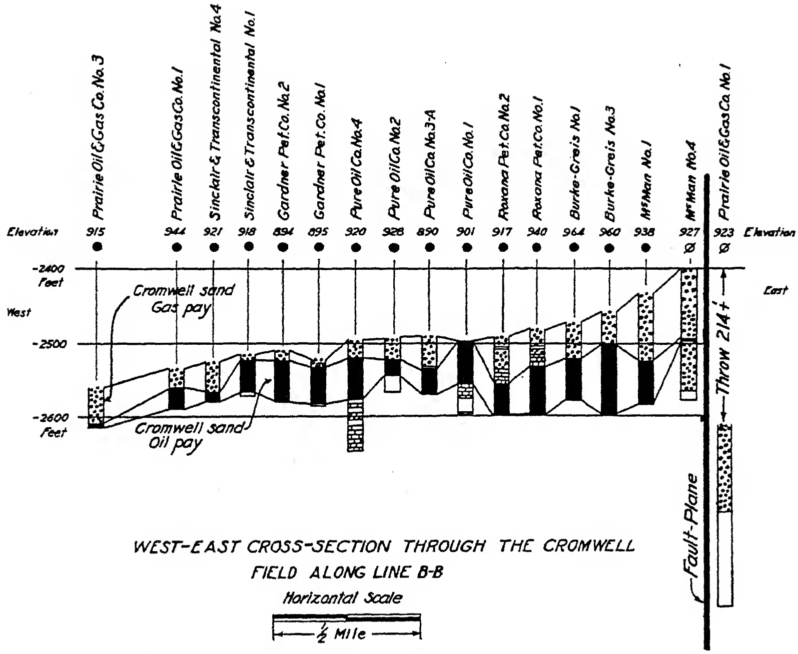

FIG. 4.—Cross section *B–B* (Fig. 3), showing large subsurface fault which is the main structural feature of the south half of Cromwell field. The fault has a downthrow toward the east of more than 200 feet, this being equivalent to 200 feet of closure.

In comparing the faults in Figures 2 and 3 it is readily noticeable that the surface faults do not carry down through the Cromwell sand. The large subsurface fault (Fig. 3) is not in alignment with any of the surface faults, but instead crosses them at an angle and has its downthrown side on the east, which is the reverse of the surface faults at this locality. Nevertheless, it is the writer's opinion that the surface fracturing and faulting is a result of subsurface folding, and probably subsurface faulting. The thickness and kind of sediments, together with forces acting at different times and in different directions, make it unnecessary to have subsurface faults directly in line with surface faults. With these same

facts in mind, we may expect subsurface folding (without faulting) to develop fractures or faults on the less competent surface rocks. Opposed to this, we may expect subsurface faults which will diminish upward and result only in a surface fold.

A south-north cross section (Fig. 5) along line *A-A* of Figure 3 is drawn through the dome of the north part of the field and shows the relation of the "Wilcox" sand to the Cromwell sand. The intervening formations are shown but are not entirely accurate, as cuttings were not kept and logging is probably poor. In drilling the "Wilcox" sand, small amounts of gas were first encountered; and on drilling farther into the sand body, the drill penetrated the oil "pay." This sand body is believed to be equivalent to the oil "pay" of the Simpson sand in the St. Louis field of the Seminole district. Careful examination of Figures 1 and 5 will reveal another sand body immediately above the "Wilcox" sand, separated from it by only a few feet of lime or sandy lime. This upper sand body is considered the equivalent of the main producing sand (Simpson sand) of the Seminole City, Searight, Bowlegs, and Little River fields. One of the most interesting facts brought out by subsurface work in this region is the convergence toward the northwest, mentioned and best illustrated by A. I. Levorsen.[1] This convergence between the Calvin sandstone and the top of the Cromwell sandstone is approximately 90 feet to the mile. There is no evidence of convergence below the Cromwell sand in this field. The convergence is in sediments of Pennsylvanian age.

RELATION OF ACCUMULATION TO STRUCTURE

The chart (Fig. 6) gives the initial daily production from the Cromwell sand, and the contour interval is 1,000 barrels per day except for the 500-barrel-per-day contour, which is dashed. In the absence of figures on production per acre, the initial production chart when compared with Figure 3 gives as true a conception of the production and its relation to structure as is obtainable. In this pool where the wells drilled into a large gas reservoir before encountering the oil "pay," it was natural that a tremendous amount of gas accompanied the oil in the flush stage of the well. For this reason very little shooting was necessary, and inasmuch as the air-gas lift was not in use at the time, the initial-production figures give a reasonably accurate idea of the flush production. This chart (Fig. 6) shows that the field is divided into two distinct areas according to initial production.

[1] "Convergence Studies in the Mid-Continent Region," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11, (1927), pp. 657–83.

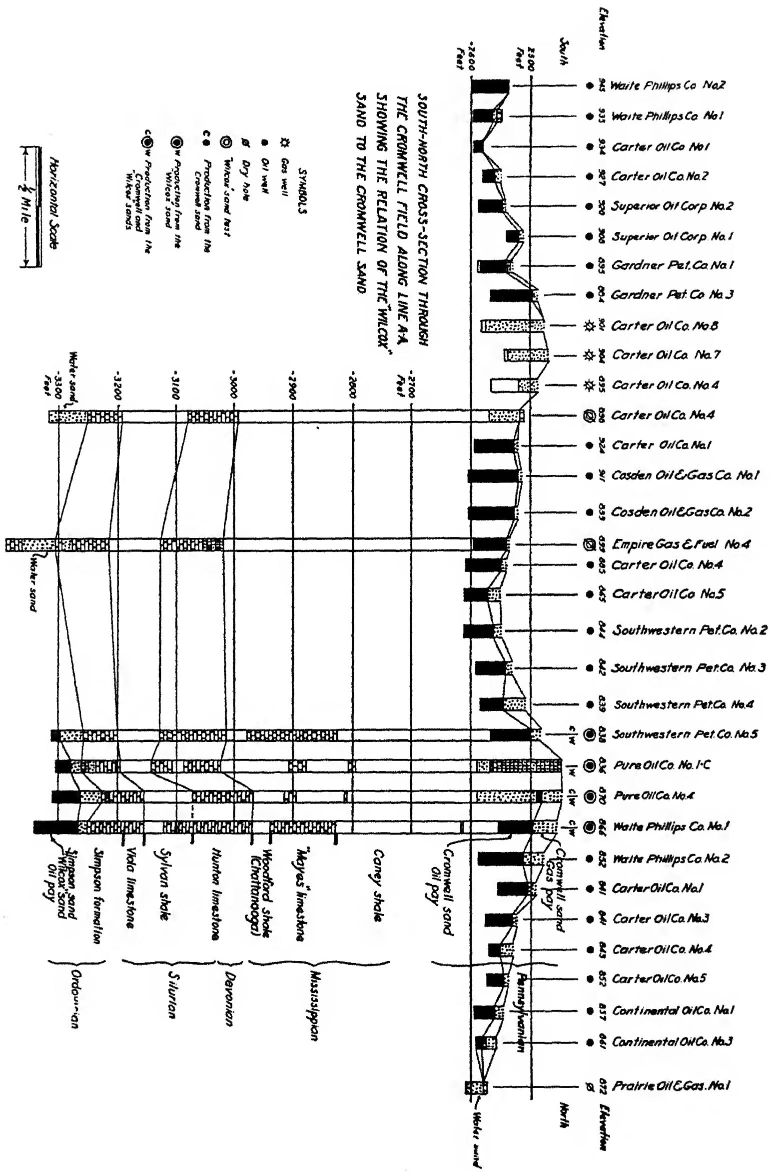

FIG. 5.—Cross section *A–A* (Fig. 3), drawn through the dome in Sec. 33, T. 11 N., R. 8 E., which is the main structural feature of the north part of Cromwell field. The relation of Cromwell and "Wilcox" sands is shown.

A partial summary of the southern area shows that one well had an initial production of more than 5,000 barrels, twelve wells had an initial production of more than 3,000 barrels, and eighteen wells had an initial production of more than 2,000 barrels per day. In the northern area, one well had an initial production of 4,000 barrels, two wells had an initial production of more than 3,000 barrels, and thirteen wells had an initial production of more than 2,000 barrels per day. A study of the contours shows the variation in production, and it is readily seen that many wells favorably located structurally were small producers.

First let us consider the southern area in which development began. The first commercial oil well was located in the northwest corner of the NE. $\frac{1}{4}$, SW. $\frac{1}{4}$ of Sec. 15, T. 10 N., R. 8 E., and development spread rapidly toward the south, north, and west. This being the fact, why was such good production obtained in the northwestern part of the area which was drilled much later than the area on the southeast? The only explanation is a good sand condition. Erratic sand conditions are more evident in the Cromwell field than in most fields. Wells on the extreme western edge of the field are located low structurally, being near the $-2,600$-foot contour which was the approximate water level of the field; and it is thought that this is the main reason for the small production. Other factors which should be considered are late date of completion (exhaustion of the gas), thinning of the sand westward, and local sand conditions. A comparison of Figures 3 and 6 shows that only small production was obtained on a structural "high" extending southwest from the center of the NE. $\frac{1}{4}$, NW. $\frac{1}{4}$ of Sec. 10, T. 10 N., R. 8 E. On the greater part of this "high," initial daily production amounted to less than 500 barrels per well, and a number of dry holes were drilled. The dry holes were completed with other wells that were drilled, and the lack of oil can not be attributed to the late date of completion or the exhaustion of gas. Samples from two of the dry holes in the southeast quarter of Section 9 showed the Cromwell horizon to be limestone, and cuttings on a third well showed the Cromwell horizon to be a sandy lime. Therefore, the principal explanation for lack of production on this structural "high" is the erratic condition of the sand body, which in at least two places graded laterally into limestone. Late date of completion of several wells caused them to be small producers, but this is of secondary importance as compared with local sand conditions. Several dry holes are shown along the fault on the upthrown side, where we should normally expect production. Although cuttings from these wells have not been examined, it is believed that late date of completion is largely the cause of their being failures, as they were completed seventeen

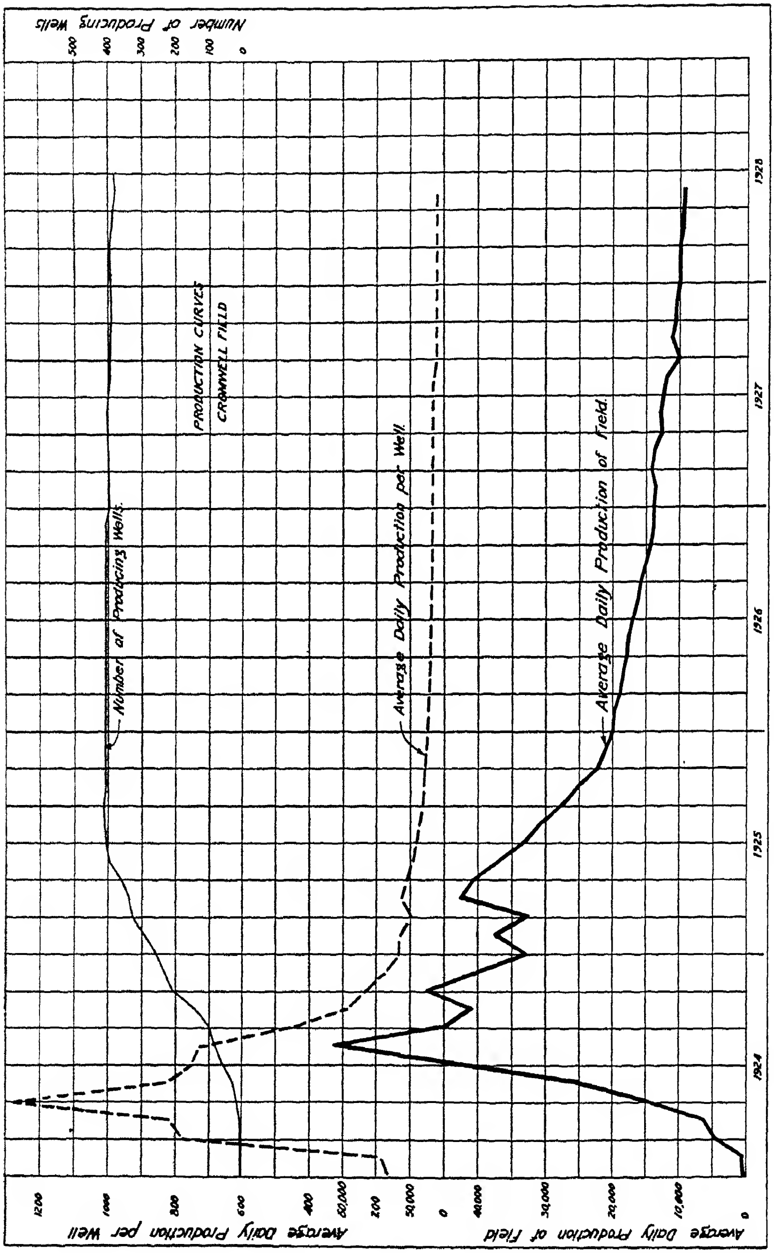

FIG. 7.—Production curves, Cromwell field.

months after the completion of the first oil well. Previous to the completion of the discovery oil well, two gas wells east of the discovery oil well had been completed in the Cromwell sand, and it was natural that the drilling campaign should proceed westward. The McMan No. 4, located near the fault (Fig. 4), best illustrates the condition. The McMan No. 1, the west offset to No. 4, was completed August 19, 1924, making 99,000-000 cubic feet of gas and 1,200 barrels of oil. The McMan No. 4, located higher structurally and probably with similar sand conditions, was completed January 19, 1925, as a dry hole, having had only 5,000,000 cubic feet of gas.

Let us now consider the northern area. All the wells on the dome in Sec. 33, T. 11 N., R. 8 E., produced less than 500 barrels of oil per day from the Cromwell sand. Cuttings from several wells showed that the sand was very tightly cemented and contained considerable lime. One well on this dome produced 60,000,000 cubic feet of gas per day, and others produced smaller amounts of gas. It is reasonable to expect that the top of this dome should be filled with gas; but as other wells were drilled, the small amount of gas and oil obtained in each well indicated very clearly that the controlling factor in the lack of production on this dome was the tight limy sand condition. Since the progress of drilling was from the south and southeast toward the north and west, it is logical to conclude that diminished gas volume caused the structurally high wells west of this dome to be small producers, even though the sand conditions became better. Other factors which have caused larger production east of this dome are the greater thickness of sand, consequently a larger oil reservoir, and the probability of more porous conditions within the sand body.

A comparison of the Cromwell sand producing area (Fig. 3) with the surface geology (Fig. 2), shows that there is a relation to the fault zone. The producing area occupies the larger part of the fault zone in Secs. 3, 10, and 15, T. 10 N., R. 8 E., a part of Sec. 34, T. 11 N., R. 8 E., and extends westward from the fault zone, which is to be expected, as the oil has undoubtedly migrated up the dip from the west. Reference to the subsurface contour map (Fig. 3) indicates that production has conformed with structure to a large extent. Production would have conformed perfectly with the structural features had erratic sand conditions not been encountered.

Since commercial production of oil from the "Wilcox" sand occurred only on the dome in Sec. 33, T. 11 N., R. 8 E., there can be no question as to the relation of production to structure in this locality. Several "Wil-

cox" sand tests were made in the south part of the field, and some of them were located favorably with respect to the subsurface contour map (Fig. 3). The fact that the two "Wilcox" sand tests in the N. ½ of Sec. 10, T. 10 N., R. 8 E., did not get commercial production deserves consideration. As shown by the map, it is possible that the fault stopped entirely at a point south of these two "Wilcox" sand tests. If this is true, there may not be any reverse dip to cause an accumulation of oil. So few "Wilcox" sand tests have been drilled in the vicinity of the fault that it is impossible to draw any reliable conclusion about the reverse dip or about the extension of the fault into the "Wilcox" sand horizon.

GREATER SEMINOLE DISTRICT, SEMINOLE AND POTTAWATOMIE COUNTIES, OKLAHOMA[1]

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ABSTRACT

The Greater Seminole district, comprising the Seminole, Searight, Earlsboro, Bowlegs, Little River, Pearson Switch, St. Louis, Mission, and Maud pools, had a total production previous to January 1, 1929, of more than 275,000,000 barrels of 40°-gravity oil since the discovery in July, 1926. This is an average recovery of 15,055 barrels of oil from each of the 17,700 producing acres, and the area is producing 400,000 barrels of oil per day (January, 1929).

The stratigraphy, structure, and geologic history are similar to the other major "Wilcox" sand pools of northern Oklahoma. Crooked holes, pre-Pennsylvanian faults, and rotary drilling have complicated the details of the geologic record. All of the pools are producing from anticlinal structures, many of which are reflected in the surface formations as minor folds, flattenings, and changes of strike.

A chapter by Ira H. Cram of The Pure Oil Company gives an idea of the detailed geological problems in the district.

ACKNOWLEDGMENTS

The writer is indebted particularly to the Oklahoma Geological Survey for permission to use in this report much of the material contained in the bulletin on the geology of Seminole County.[3] In the preparation of that report, the ideas of many of the geologists working with the problems of the Seminole area were used, and the writer again acknowledges his indebtedness to them.

The Amerada Petroleum Corporation, the Indian Territory Illuminating Oil Company, the Gypsy Oil Company, and the Darby Petroleum Company kindly permitted the publication of their surface maps of the several oil fields; Ira Cram of the geological department of The Pure Oil Company prepared the section of this report dealing with Sec. 14, T. 8 N., R. 6 E., Bowlegs pool, and the type logs of three of the fields; and J. M. Dale of the Independent Oil and Gas Company prepared the block diagram of the Pearson and St. Louis fields. The writer gratefully acknowledges these contributions. In addition, thanks are due the Independent Oil and Gas Company for permission to publish this report.

[1] Manuscript received by the editor, January 23, 1929.

[2] Chief geologist, Independent Oil and Gas Company.

[3] A. I. Levorsen, "The Geology of Seminole County," *Oklahoma Geol. Survey Bull. 40-BB* (1928).

The reader is referred to the report by Morgan[1] for a more detailed description of the stratigraphy of the area as it is found in the outcrops around the Arbuckle Mountains, to the paper by Powers[2] for a description of the conditions in the Seminole area one year after its discovery, and to the Bureau of Mines report on the Seminole pool[3] for a description of the stratigraphy and operating conditions.

GENERAL

The Greater Seminole district covers an area of approximately 400 square miles in Seminole and Pottawatomie counties, south-central Oklahoma. The principal producing oil fields, in the order of their discovery, are St. Louis, Seminole City, Searight, Earlsboro, Bowlegs, Pearson Switch, Little River, and Mission. There are several other areas in which oil has been discovered in commercial quantities but which are at present shut in, awaiting more favorable market conditions. The locations of the oil fields and the development in the Greater Seminole district are shown in Figure 1.

With the exception of the lenticular Earlsboro sand in the Earlsboro pool, which is of Pennsylvanian age, all of the commercial production is found in the Misener sand (basal Mississippian age), in the Hunton formation (Devonian-Silurian age), and in the Simpson formation (Ordovician age). The daily production from these horizons reached a total of 527,000 barrels per day in July, 1927, and the present average production is approximately 325,000 barrels per day (January 1, 1929). The total production of this area was more than 275,000,000 barrels of oil up to January 1, 1929, from 1,700 wells. The detail statistics of the production records of the pools are shown in Table I.

SURFACE FORMATIONS

Shales, sandstones, conglomerates, and limestones of upper Pennsylvanian age compose the rocks exposed in the Greater Seminole area. The succession of these rocks shown in Figure 2 is a comparison of the section in the north part of the area with that of the south side.

The Pawhuska limestone crops out through R. 6 E. It is generally used as the datum horizon in mapping the surface structure in that area.

[1] George D. Morgan, "Geology of the Stonewall Quadrangle, Oklahoma," *Oklahoma Bur. of Geol. Bull.* 2 (1924).

[2] Sidney Powers, "The Seminole Uplift, Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 1097–1108.

[3] C. R. Swartz, C. R. Bopp, and W. S. Morris, "Preliminary Engineering Report on the Seminole Pool, Seminole County, Oklahoma," *U. S. Bur. Mines* (1928).

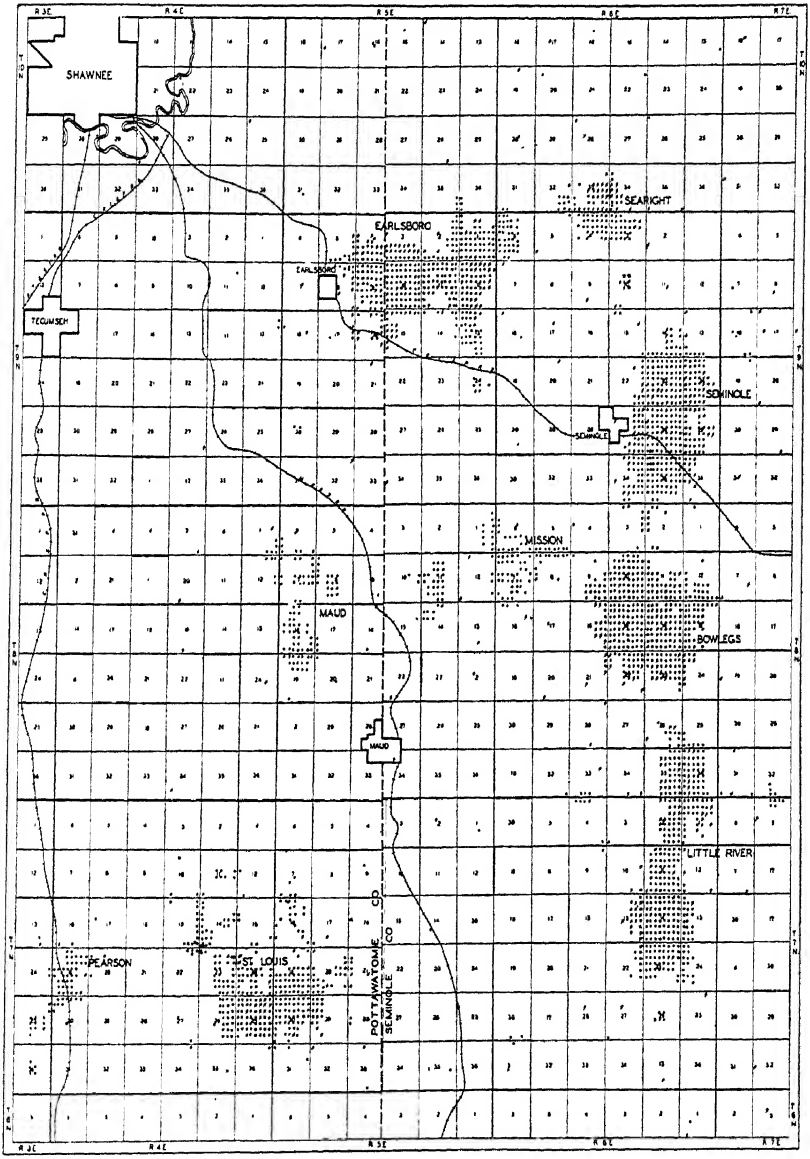


FIG. 1.—Location of oil fields and development in Greater Seminole area. Width of area mapped, 21 miles. Since this map was drawn new production has been developed in the following sections: Sec. 18, T.9N., R.6E., Sec. 18, T.9N., R.7E., Sec. 26, T.8N., R.6E., and Secs. 16 and 17, T.7N., R.4E.

TABLE I

STATISTICAL DETAILS OF GREATER SEMINOLE OIL POOLS

	Seminole City	Searight	Earlsboro	Bowlegs	Little River	Pearson Switch	St. Louis
Discovery of commercial production	Hunton ls., Mar. 7, 1926, I.T.I.O., Jones 1, 24-9-6 "Seminole" ss., July 16, 1926, Indpt. O.&G., Fixico 1, 26-9-6	Hunton ls., Apr. 21, 1926, Searight, Youngblood 1, 33-10-6 "Seminole" ss., Oct. 11, 1926, Searight, Youngblood 3, 33-10-6	Earlsboro ss., Mar. 1, 1926, Morgan & Flynn, Ingram 1, 10-9-5 "Seminole" ss., Dec. 3, 1926, Gypsy, State 1, 16-9-5	"2,400-Foot" Gas, Jan. 18, 1926, I.T.I.O., Goforth 1, 15-8-6 "Seminole" ss., Jan. 4, 1927, I.T.I.O., Davis 1, 13-8-6	"Seminole" ss., July 1, 1927, I.T.I.O., House 1, 1-7-6	Hunton ls., Jan. 14, 1927, Wrightsman Petr. Co., Davis 1, 30-7-4 Viola, Oct. 24, 1927, Magnolia, Harper 1, 25-7-3	Hunton ls., Jan. 13, 1926, Indpt.-Darby, Davis 1, 15-7-4 "Wilcox," Apr. 27, 1928, Magnolia, Hembree 1, 19-7-5
Initial production of wells, in barrels	Max., 9,000 Av. 2,500	Max., 5,000 Av., 1,500	Max., 14,000 Av., 2,500	Max., 8,000 Av., 2,500		Max., 3,200 Av., 750	"Wilcox," Max., 20,000 Av., 5,000
Drilling depths, in feet	Hunton ls., 3,850 "Seminole" ss., 4,000-4,400	Hunton ls., 4,000 "Seminole" ss., 4,300-4,400	Earlsboro ss., 3,500 "Seminole" ss., 4,250-4,400	"Seminole" ss., 4,000-4,300	"Seminole" ss., 4,150-4,500	Hunton ls., 3,700-3,850	Hunton ls., 3,600-3,700 "Wilcox" 4,150-4,300
Age of fields, Jan. 1, 1929, in months	29½	26½	25	24	18	23½	35½
Area producing to Oct. 1, 1928, in acres	3,520	740	3,440	3,400	3,200	570	3,400

TABLE I—*Continued*

	Seminole City	Searight	Earlsboro	Bowlegs	Little River	Pearson Switch	St. Louis
Total gross production to Jan. 1, 1929, in barrels	72,560,269	18,092,730,	70,590,268	62,502,623	29,916,229	2,617,931	20,203,802 (13,540,450 from "Wilcox")
No. of wells drilled:							
Dry	37	19	66	41	37		
Abandoned	70	6	51	24	0		
Producing, Jan. 1, 1929	282	68	293	312	321		(68 "Wilcox" wells)
Total	389	93	410	377	358	57	282
Total production per well, Jan. 1, 1929, in barrels	206,421	244,496	205,204	186,019	93,196	45,928	71,290 ("Wilcox" wells 199,912)
Maximum daily production in barrels, during week ending	Feb. 28, 1927 211 wells 253,192	June 21, 1927 42 wells 39,857	Aug. 9, 1927 135 wells 205,286	Aug. 2, 1927 173 wells 190,403	Oct. 1, 1928 257 wells 136,698		Sept. 20, 1928 230 wells 130,155 (25 "Wilcox" wells, 85,000)
Average production in barrels per producing acre to Jan. 1, 1929	20,642	24,450	20,520	18,019	9,320	4,593	7,120 ("Wilcox," 19,912)

Total production to Jan. 1, 1929, barrels.................... 276,483,852
Total area producing, acres.................... 17,700
Average yield per acre, Greater Seminole, barrels.................... 15,055

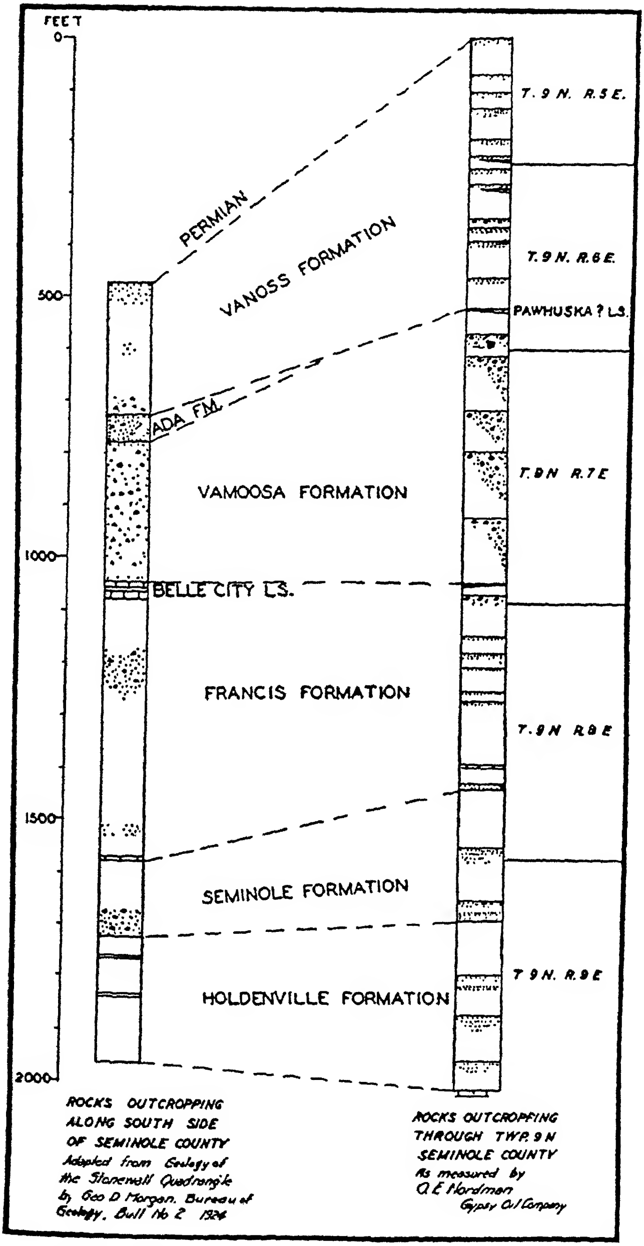


FIG. 2.—Geologic section showing nature of formations exposed in southern and central Seminole County. From "Geology of Seminole County," *Oklahoma Geol. Survey Bull. 40-BB* (1928).

SUBSURFACE FORMATIONS

PENNSYLVANIAN ROCKS

Rocks of Pennsylvanian age extend below the surface to depths ranging from 3,000 to 4,000 feet and consist of alternating shales, sands, conglomerates, and thin limestones. In the Earlsboro field the Pennsylvanian rocks with a total thickness of 3,840 feet consist of shale (77 per cent), sand (19 per cent), and limestone (3 per cent). With but few exceptions, the rotary drilling method has been used; consequently, knowledge of the details of the Pennsylvanian stratigraphy is limited. The "Calvin sands," which form a prominent marker farther east, can be traced through the Seminole area only with difficulty. They are found at depths ranging from 2,500 to 3,200 feet below the surface and, although relatively poor, offer the best datum for mapping the Pennsylvanian structure below the surface.

Farther east the lower part of the Pennsylvanian is of Pottsville age and consists of the Gilcrease formation (correlated with the Atoka formation) and the Wapanucka formation. The latter consists of the Wapanucka limestone and the underlying Cromwell sand. Because of early Pennsylvanian uplift, erosion, and overlap, the Gilcrease and Wapanucka formations are absent in the Greater Seminole area with the exception of the Little River field. The base of the Pennsylvanian in the remainder of the area is marked by an unconformity which transgresses upward across the section from east to west. This unconformity is identified in well cuttings by the presence of a sandy shale with a maximum thickness of 40 feet, containing subangular to rounded sand grains, weathered chert, traces of glauconite, lignite fragments, and other conglomeratic material. Round frosted sand grains resembling those of sandstones in the Simpson formation are found.

Oil and gas from Pennsylvanian sands have been found in the following areas:

Secs. 30 and 31, T. 7 N., R. 6 E. (little oil); 1,200± feet; Stray sand
Sec. 15, T. 8 N., R. 6 E. (gas); "Calvin" series
Secs. 10 and 11, T. 9 N., R. 5 E. (commercial oil); 3,500 feet; Earlsboro sand
Sec. 26, T. 7 N., R. 6 E. (commercial oil); Cromwell sand

Type logs of the formations found in wells in the Little River, Bowlegs, and Seminole City fields are shown in Figure 3. They were prepared from samples of the well cuttings by Ira H. Cram, of The Pure Oil Company. Table II shows the thicknesses of the formations in the several oil

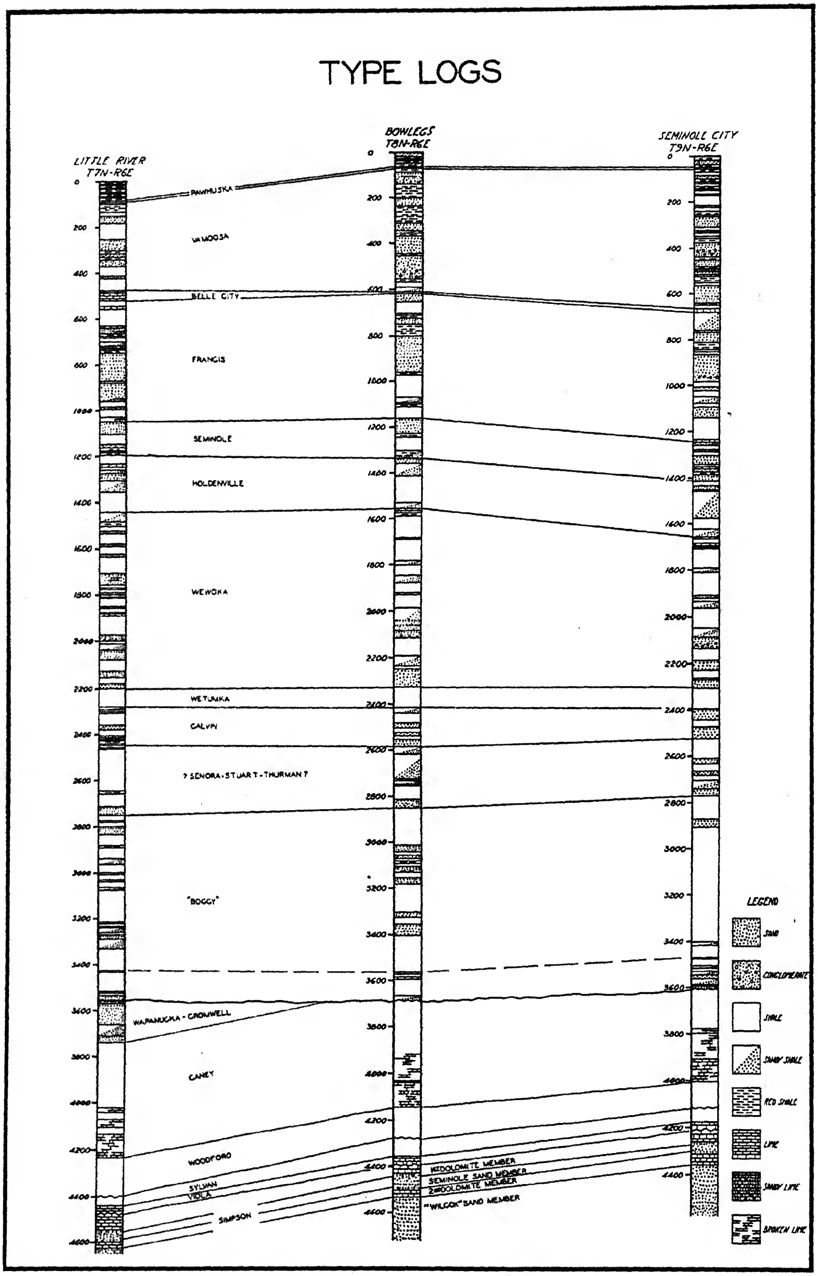


FIG. 3.—Type logs from Little River, Bowlegs, and Seminole fields. Prepared from well cuttings by Ira H. Cram, The Pure Oil Company. Depths shown in feet.

fields and Table III is a generalized geologic section of the Greater Seminole district.

MISSISSIPPIAN ROCKS

CANEY FORMATION

In the Seminole district the Caney formation includes the beds lying between the base of the Pennsylvanian and the top of the Chattanooga shale. The lower 90–110 feet is locally termed the "Mayes" limestone member, and the shales above it are called the Caney shale.

TABLE II

SUMMARY OF DETAILS OF STRATIGRAPHY OF PRODUCING FIELDS OF GREATER SEMINOLE AREA. (Thicknesses in feet).

	Seminole	Searight	Earlsboro	Bowlegs	Little River	Pearson Switch	St. Louis
Pennsylvanian....	3,400–3,600	3,700–3,900	3,800–3,900	3,300–3,500	3,200–3,500	3,700–3,800	
Caney shale......	150–400	200–300	20–200	150–450	300–400(?)	Absent	
"Mayes" lime....	90–110	90–100	90–100	90–100	90–100	0	0–120
Chattanooga shale	90–110	40–60	100–125	120–150	165–175	0–50	0–220
Hunton lime.....	0–75	85–160	0–30	0–5	0	30–370	0–414
Sylvan shale.....	80–100	70–100	90–110	60–90	40–60	80–100	50–90
Top of Viola to top "Seminole" sand	70–110	75–105	80–110	70–135	60–140 (Increases southward)		
"Seminole" sand..	40–80		50–100	40–100	0–60	0	0
Top of Viola to top "Wilcox" sand..	170–220		170–200	210–250	225–275	?	230–280

Caney shale member.—As observed in well cuttings, the upper shale member is bluish-gray, uniformly fine-grained, fissile shale. It is easily drilled, but it caves readily. It is slightly calcareous and contains small amounts of finely disseminated pyrite. Near the base it is more granular and evidently grades into the lower calcareous member, locally known as the "Mayes" limestone.

"Mayes" limestone member.[1]—The "Mayes" limestone is a black to brown, finely crystalline, highly calcareous shale or argillaceous limestone.

[1] This may be equivalent to the Mayes limestone of northeastern Oklahoma.

TABLE III

Generalized Geologic Section, Greater Seminole District

(The formations below the Belle City limestone are known only from well logs)

System	Formation		Thickness in Feet	Character of Sediments
Quaternary	Recent		0–40	Alluvium, sand, clay, and conglomerate
				Unconformity
	Pleistocene			Guertie sand and gravel
				Unconformity
Pennsylvanian	Vanoss formation		250–500	Shale, arkosic sand, and conglomerate
	Ada formation		0–50	Sand and shale. Thins out northward
	Vamoosa formation		270–525	Conglomerates, sands, shale. Thins southward
	Belle City limestone		0–30	Gray, fossiliferous limestone. Thins northward
	Francis formation		370–500	Shale with interbedded sandstone layers
	Seminole formation Holdenville shale Wewoka formation		800–1,000	Shale with interbedded sandstone layers
	Wetumka shale Calvin sandstone		250–300	"Calvin sand series" of well logs. Persistent series of sands extending from base of Calvin sandstone to top of basal sand of Wewoka formation
	Boggy formation McAlester shale		600–1,400	Shale with several variable sandstones including Earlsboro sand
				Unconformity—structural and erosional
	Pottsville Wapanucka	Wapanucka limestone	0–40	Present only in
		Cromwell sand	0–100	Little River area
				Unconformity—structural and erosional
Mississippian	Caney formation	Caney shale member	0–600	Bluish gray, fine-grained shale overlain unconformably by formations up to Boggy shale. Absent in Pearson pool
		"Mayes" limestone member	90–110	Argillaceous, black to brown limestone. Sycamore limestone at base. Absent in Pearson pool
				Unconformity(?)
	Chattanooga shale Misener sand at base		20–250	Uniform, black shale, thickens southward. Woodford chert of Arbuckle Mountain section. Absent or thin in Pearson pool
				Unconformity—structural and erosional
Devonian	Bois d'Arc limestone Haragan shale			Hunton limestone of oil fields. Produces oil from weathered zone near top or from porous horizons. Generally not differentiated in wells. Faunal hiatus separates each member below Haragan shale
Silurian	Henryhouse shale Chimneyhill limestone Pink crinoidal member Glauconitic member Oölitic member		0–415	

TABLE III—*Continued*

<table>
<tr><th>System</th><th colspan="2">Formation</th><th>Thickness in Feet</th><th>Character of Sediments</th></tr>
<tr><td rowspan="7">Ordovician</td><td colspan="2">Sylvan shale</td><td>35–100</td><td>Gray-green shale</td></tr>
<tr><td colspan="2">Viola limestone (Fernvale)</td><td>20–40</td><td>White to gray limestone
Unconformity</td></tr>
<tr><td rowspan="5">Simpson formation</td><td>Dense lime member</td><td>5–50</td><td></td></tr>
<tr><td>First dolomite member</td><td>30–125</td><td></td></tr>
<tr><td>"Seminole" sand member</td><td>0–80</td><td>Main producing horizon. "First Wilcox"</td></tr>
<tr><td>Second dolomite member</td><td>15–100</td><td></td></tr>
<tr><td>"Wilcox" sand member</td><td>500+</td><td>Locally productive "Second Wilcox"</td></tr>
</table>

It does not cave, and it is easily drilled. At the base occurs a non-uniform, thin, gray limestone bed, and this is underlain by a very persistent layer containing considerable glauconite and some sand grains.

A few micro-fossils are found in the Caney formation. The following fossils have been observed: *Hindeodella* sp., *Caneyella wapanuckensis*, *Orthoceras* sp., and *Kirkbya* sp.

The known thickness of the Caney formation, except in the Pearson Switch area where it has been removed, ranges from 120 to 700 feet, depending on the depth of the post-Mississippian erosion. Of this thickness, the lower or "Mayes" limestone member ranges uniformly from 90 to 110 feet in thickness. The upper shales range from 20 to 600 feet in thickness, the thin areas being high structurally and the thick areas, low structurally.

The Caney formation is overlain unconformably by rocks of Pennsylvanian age. This unconformity is both structural and erosional, the erosion in places having removed as much as 600 feet of Caney shale prior to the deposition of the Pennsylvanian sediments. During this period of erosion the Caney shale was removed from the western part of the St. Louis pool; and the Caney shale, the "Mayes" limestone, and, in places, all of the Chattanooga shale were removed in the Pearson Switch pool. Thus in T. 7 N., R. 4 E., the Pennsylvanian sediments overlie rocks ranging in age from Hunton (Devonian-Silurian) to Caney shale (upper Mississippian).

The Pennsylvanian formation which overlies the Caney formation is probably equivalent in age either to the McAlester or Boggy formation. Evidently faulting and folding occurred during post-Mississippian or early

Pennsylvanian time, followed by base-leveling and the progressive westward overlap of the Pennsylvanian formations. Thus the structurally higher parts of the Mississippian were eroded to a greater depth than those areas which were structurally low and protected. The presence of the persistent glauconite layer and the local sandy phases at the base of the "Mayes" limestone member indicate that a stratigraphic break separates it from the underlying Chattanooga shale.

The Caney formation of Seminole County is correlated with the lower or Mississippian Caney shale of the Arbuckle Mountain region on the south, which in turn has been correlated by Girty[1] as being lithologically and faunally similar to the Moorefield shale of northern Arkansas. The "Mayes" limestone member of the Caney formation can be traced northward by well cuttings and correlated with the black Mississippi limestone of the Ponca City district. The variable white limestone layer occurring at the base of the "Mayes" limestone member is undoubtedly represented in the Arbuckle Mountain section by the Sycamore limestone of Kinderhook age.

CHATTANOOGA SHALE

The Chattanooga shale as observed in well cuttings is black noncalcareous, uniformly fine-grained shale. It contains a large amount of coarsely crystalline pyrite in irregular nodules. Local occurrences of black chert have been noticed. In drilling it resembles the overlying "Mayes" limestone member of the Caney formation and is not as a rule distinguished from it by the drillers.

The following micro-fossils are known to occur in the formation: Mississippian conodonts and many *Sporangites huronense.*

The thickness of the formation ranges from 30 to 40 feet in the north part of the county and attains a maximum of 100 feet at Earlsboro, 165 or more feet in the Little River field, and more than 200 feet at the south side of the area. In the center of the Pearson Switch pool, however, the Chattanooga shale has been entirely removed by post-Mississippian erosion, and the Pennsylvanian sediments rest directly on the Hunton limestone. The Chattanooga shale is normally overlain by the "Mayes" limestone member of the Caney formation which contains glauconite and local sandy layers at its base, which indicate a stratigraphic break. The base of the Chattanooga shale rests with erosional and angular unconformity upon beds ranging in age from middle Sylvan to upper Hunton.

[1] George H. Girty, "The Fauna of the Moorefield Shale of Arkansas," *U. S. Geol. Survey Bull. 439* (1911).

The varying thickness of the Chattanooga shale is shown in Figure 4.

In the field, the names "Chattanooga shale" and "Woodford shale" are both used. The term "Chattanooga shale" is preferable, since as a subsurface formation it is better established in Oklahoma and is well known and widespread in the east-central United States. The age of the Chattanooga shale was originally determined as Upper Devonian and is still considered as such by the United States Geological Survey. Geologists in increasing number, however, believe that from both paleontological evidence and stratigraphic relations it bears a closer relation to the Mississippian and should be considered as the basal member of that system. The major unconformity at its base and the Mississippian fossils found in the formation in the Seminole district are the basis for placing it in the Mississippian system in this paper.

A few feet of sand resembling the Simpson sand is found locally at the base of the Chattanooga shale. This sand farther north in Oklahoma is called the Misener sand. In some areas, particularly in the Bowlegs and Little River fields, it contains a considerable amount of limestone. Minor quantities of oil have been produced from the Misener sand in the Seminole district, but recently (November, 1928) very important production from this sand was discovered in the Maud area, in a new field developed in this horizon in the western part of T. 8 N., R. 5 E. Luther H. White's description of it in northern Oklahoma applies to the few occurrences in the Seminole area. He states:

> A surprisingly small amount of erosional débris was left upon this old eroded surface. However, there were a few sand dunes composed of sand derived from the Simpson formation. In addition to a few well developed dunes a thin veil of wind-blown sand was scattered over broad areas. This sand was preserved by the deposition of the Chattanooga shale above it. Where it is exposed in eastern Oklahoma and Arkansas it is known as the Sylamore sandstone. By the drillers in the oil country, it is called the "Misener" sand. Because of its source of origin, therefore, samples of it from wells resemble samples from the "Wilcox" or "Burgen." It is extremely lenticular in extent. Wells drilled to this sand are often dry, even though higher structurally than offset wells producing from it, because of its absence. Where the "Misener" is sufficiently wide-spread for structure to affect the accumulation of oil, it produces on domes or anticlines. In most cases, however, it produces as a true lense without reference to structure.[1]

[1] Luther H. White, "Subsurface Distribution and Correlation of the Pre-Chattanooga ("Wilcox" Sand) Series of Northeastern Oklahoma," *Oklahoma Geol. Survey Bull. 40* (1926), p. 22.

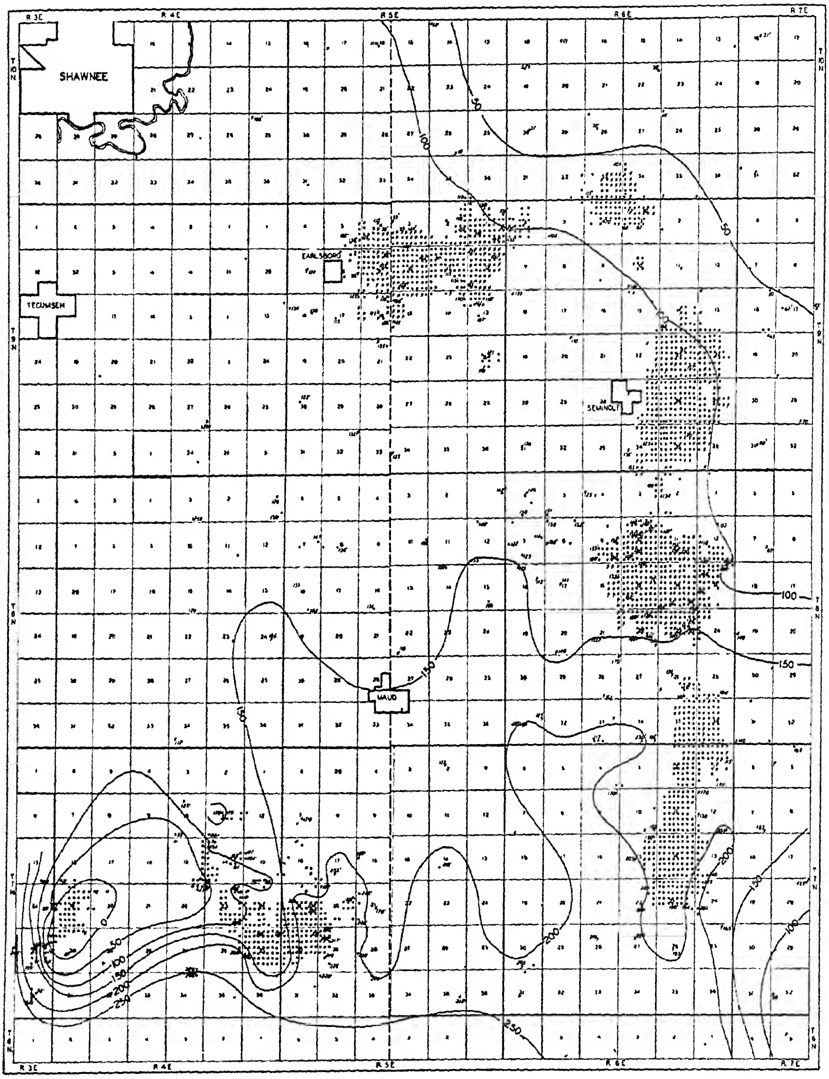


FIG. 4.—Thickness of Chattanooga shale, Greater Seminole district. Contour interval, 50 feet. Width of area mapped, 21 miles.

DEVONIAN-SILURIAN ROCKS

HUNTON FORMATION

The Hunton formation, or Hunton limestone as it is commonly called, where occurring as a full section in the Seminole district, ranges from light gray to white, fine-grained, cherty limestone at the top (Bois d'Arc member) to darker gray, crystalline limestone at the base (Chimneyhill member). Locally each of the three members into which the Chimneyhill or lower Hunton is divided, the pink crinoidal member, the glauconitic member, and the oölitic member, have been identified in well cuttings. The average Hunton limestone is difficult to separate from the Viola limestone by its physical appearance in well samples. Its position in the geologic section below the black Chattanooga shale and above the green to gray Sylvan shale and its content of many micro-fossils, in general, offer the best evidence for its identification.

The Hunton formation contains a wide variety of micro-fossils, particularly ostracods and crinoids of which but few are as yet known to be diagnostic of individual beds. It is of interest to note that the systemic boundary between the Silurian and Devonian occurs within the Hunton limestone.

Depending on the post-Hunton erosion and the extent of the unconformities within the Hunton formation, the thickness ranges from almost nothing to 415 feet. Where the Hunton is thin, the lower or Chimneyhill member is the division encountered, and this indicates that the principal reason for the change in thickness is the erosion of the upper members. Throughout a large, irregular area across central Seminole County the Hunton is absent or very thin, as shown in Figure 5. Apparently a broad, irregular arch extended through this area at the end of Hunton time, the crest having been eroded during the peneplanation which preceded the deposition of the Chattanooga shale.

The upper contact of the Hunton formation is an erosional and gently angular type of unconformity, the Chattanooga shale resting on the different members of the Hunton formation or upon the underlying Sylvan shale, depending on the depth of the erosion. There was also some topographic relief in the Pearson Switch and St. Louis districts as evidenced by the variable thickness of the Chattanooga where overlain by the "Mayes" limestone (Fig. 4). The Hunton limestone rests conformably on the Sylvan shale.

The Hunton formation crops out on the north side of the Arbuckle Mountains 20 miles south of Seminole County. Reeds[1] has subdivided it

[1] Chester A. Reeds, "The Hunton Formation of Oklahoma," *Amer. Jour. Sci.*, Vol. 32 (October, 1911).

limestone and Haragan shale) in the Devonian, and the two lower formations (Henryhouse shale and Chimneyhill limestone) in the Silurian system. Reeds[1] later subdivided the Bois d'Arc limestone into the Frisco formation at the top and the Bois d'Arc limestone below. Evidence of the unconformities within the Hunton formation as described by Reeds is not generally observed in well cuttings from the Hunton limestone in the Seminole district.

Oil in commercial quantities has been found in the Hunton limestone of the Seminole district in the Searight, Seminole, Pearson Switch, and St. Louis fields. The oil occurs in solution cavities, small vugs, fissures, and other secondary features in the limestone. As it is commonly found near the top of the formation, it is probable that the porosity is in part an effect of the pre-Chattanooga weathering and erosion.

ORDOVICIAN ROCKS

SYLVAN SHALE

The Sylvan shale as observed in well cuttings is a gray to light gray, uniformly fine-textured shale. The upper 5 or 10 feet is characteristically light green but, because of pre-Chattanooga erosion, is absent in many areas. The Sylvan shale is easily and rapidly drilled but caves readily when wet. It effervesces slightly in dilute hydrochloric acid. It contains finely disseminated pyrite. The basal 5–10 feet is darker, more calcareous, locally sandy, and in one well[2] was found to contain considerable arkosic material. The Sylvan shale has a soapy or slippery feel when wet.

Graptolites of Medina age[3] are found in the basal 5 or 10 feet; otherwise the Sylvan shale is unfossiliferous.

The thickness of the Sylvan shale ranges from 30 to 130 feet. The Sylvan is in general thickest where overlain by the Hunton limestone and thin where pre-Chattanooga erosion has removed the Hunton limestone and the upper part of the Sylvan shale. Since nearly all of the wells are remeasured at the base of the Sylvan shale or the top of the Viola limestone, the variable thickness reported in some wells is not real but is due to the correction of the drilling measurement.

The Sylvan shale is normally overlain conformably by the Hunton formation. Throughout the central part of the area, where pre-Chattanooga erosion has removed the Hunton limestone, the Chattanooga shale

[1] Chester A. Reeds, "The Arbuckle Mountains, Oklahoma," *Natural History*, Vol. 26, No. 5 (1926).

[2] Ira Cram, personal communication.

[3] George S. Buchanan, personal communication.

rests with erosional and slightly angular unconformity on different horizons of the Sylvan shale, depending on the depth of erosion (Fig. 5). The Sylvan shale rests conformably on the Viola limestone unless the lithologic change at the base of the Sylvan shale and at the top of the Viola limestone can be construed as indicating a break in sedimentation.

The Sylvan shale has been considered to be Upper Ordovician in age and is still so considered by the United States Geological Survey.[1] Ulrich[2] believes it to be of Silurian age, and his most recent paper[3] on the problem presents a very convincing argument in favor of such a change.

VIOLA LIMESTONE

The Viola limestone is generally used as the datum in mapping Ordovician structure. It is white to gray, coarsely crystalline limestone ranging from 30 to 75 feet in thickness. The upper 5–10 feet is milky white, flaky, and soft. The crystalline limestone is denser, drills hard, and furnishes an excellent casing seat. The Viola limestone contains no dolomite and effervesces strongly in dilute hydrochloric acid.

The Viola limestone contains very few micro-fossils in contrast to the highly fossiliferous Hunton limestone. Some crinoid stems and some simple ostracods have been found in it.

The Sylvan shale rests conformably on the Viola limestone unless the lithologic change at the base of the Sylvan and the white, flaky upper part of the Viola limestone is interpreted as indicating a stratigraphic break. Locally the Viola limestone seems to be conformable on the underlying Simpson formation, but throughout broad areas it overlaps the entire middle and lower Viola and the upper Simpson section.

Fanny C. Edson[4] states that the Viola limestone of the Mid-Continent "consists of two members, an upper, coarsely crystalline, Richmond bed, and a lower dense, buff, 'lithographic' bed, probably upper Black River in age." This dense lithographic limestone underlies the Viola limestone in the Seminole area and is here considered as the upper member of the Simpson formation. The exact stratigraphic position of this limestone has not been determined, and either interpretation may be correct. In the Seminole district the dense limestone member seems to be

[1] "Geologic Map of Oklahoma," *U. S. Geol. Survey* (1926).

[2] E. O. Ulrich, "Revision of the Paleozoic Systems," *Bull. Geol. Soc. Amer.*, Vol. 22 (1911).

[3] "Relative Values of Criteria Used in Drawing the Ordovician-Silurian Boundary," *ibid.*, Vol. 37, No. 2 (June, 1926).

[4] "Ordovician Correlations in Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 968–70.

more closely associated with the Simpson formation than with the Viola limestone, and the "top of the Simpson" as commonly reported in the field is the top of the dense brown limestone.

The Viola limestone is considered to be of Ordovician age by the U. S. Geological Survey.

Ulrich[1] states that the Viola limestone observed throughout east-central Oklahoma is the Richmond phase of the Viola limestone of the Arbuckle Mountains and White[2] correlates it with the Fernvale limestone of Arkansas. Ulrich[3] places the Richmond, consequently this upper phase of the Viola limestone, in the Silurian system.

SIMPSON FORMATION

In the Seminole district the Simpson formation, graphically shown in Figure 6, consists of several members in descending order as follows:

Dense limestone member
First dolomite member
"Seminole" sand member.........."First Wilcox" or "Simpson sand" of oil fields
Second dolomite member
"Wilcox" sand member............"Second Wilcox" sand of oil fields

Dense limestone member.—This is dense, brown to gray, lithographic limestone, locally containing thin dolomitic layers. Micro-fossils are plentiful, particularly ostracods, but very few of them have been described. It underlies the white to gray, coarsely crystalline Viola limestone and is readily distinguished from it by the drillers. It is reported in the well logs as the "top of the Simpson." It ranges in thickness from 5 to 50 feet, the average thickness being approximately 15 feet.

First dolomite member.—This is a gray to brownish-gray, finely crystalline dolomite. It is of lighter color and coarser texture than the dense limestone member. These features, together with its greater magnesian content, offer a means of recognizing it. The lower 5–10 feet in the producing fields is more coarsely crystalline, very hard, and contains increasing amounts of Simpson sand grains with depth. It ranges in thickness from 15 to 50 feet, the average thickness being 25 feet.

[1] E. O. Ulrich, quoted by F. L. Aurin, G. C. Clark, and E. A. Trager, "Subsurface Pre-Pennsylvanian Stratigraphy," *Bulletin Amer. Assoc. Petrol. Geol.* Vol. 5 (1921), pp. 149–50.

[2] Luther H. White, *op. cit.*, p. 18.

[3] E. O. Ulrich, "Relative Values of Criteria Used in Drawing the Ordovician-Silurian Boundary," *Bull. Geol. Soc. Amer.*, Vol. 37, No. 2 (June, 1926).

"Seminole" sand member.—This is the most important producing horizon of Seminole County. It consists of a bed of uniformly fine-grained, slightly dolomitic sandstone whose maximum thickness is 80 feet. The sand grains are subangular to rounded, many of the round grains being larger and frosted or etched. The "Seminole" sand is alternately hard and soft, the greater production generally coming from the softer horizons. The hardness of layers is probably caused by local cementation or dolomitization; the softer parts are less consolidated. It is also called the "First Wilcox" and "Simpson sand" and is not to be confused

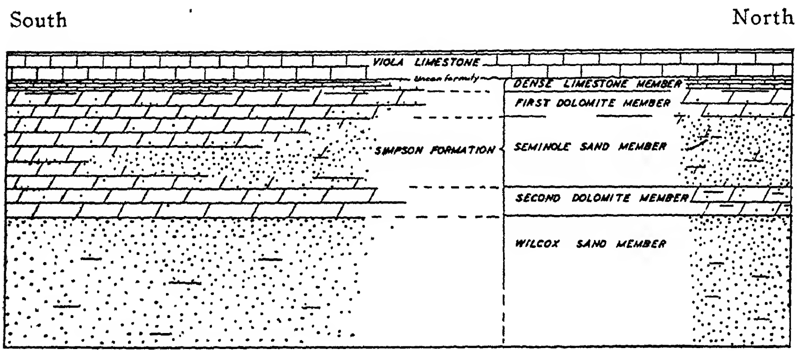


FIG. 6.—Ideal diagram of relations of members of Simpson formation in Seminole district. From "Geology of Seminole County," *Oklahoma Geol. Survey Bull. 40-BB* (1928).

with the Seminole conglomerate of Pennsylvanian age, which crops out farther east in Seminole and Hughes counties.

The "Seminole" sand member is probably a lens, grading into dolomite toward the southern part of the area and thinning out toward the north and northeast parts of the state either by erosion and overlap of the overlying Viola limestone, non-deposition, or gradation into dolomite. It is differentiated in well cuttings from the true "Wilcox" sand by its dolomite content and the greater uniformity and slightly smaller size of its sand grains.

Second dolomite member.—Below the "Seminole" sand member is found a dolomite, sandy dolomite, or interstratified shale and dolomite ranging from 10 to 100 feet in thickness. It is persistent throughout the Seminole district, the thicker beds being found where the "Seminole" sand is thin or absent as in the southern part of the area. There it is not distinguished from the first dolomite member.

The first four members of the Simpson formation comprise the post-"Wilcox" Simpson, as described by Luther White.[1]

"Wilcox" sand member.—The main sand body of the Simpson formation is found below the second dolomite member, or from 150 to 250 feet below the top of the Viola limestone. Wells in the Seminole and Wewoka fields have penetrated it to a depth of 217 and 675 feet, respectively, and have not encountered the base. In both fields it was found to be interstratified with thin layers of green shale. The upper few feet, in all wells which are known to have reached it, characteristically consist of relatively coarse sand grains. Dolomitic layers have been found, but they are not common as in the "Seminole" sand member. It produces large amounts of oil in local dome folds in the St. Louis area and is irregularly productive in the other fields of the area.

PENNSYLVANIAN STRUCTURE

The structure at the surface is in general monoclinal and comprises a part of the gently westward-dipping Prairie Plains monocline which extends from Iowa to Texas. Detailed mapping of the structure shown at the surface discloses numerous minor changes in strike, rate of dip, and minor faulting. Most of the producing oil fields are found in these areas of irregular surface structure. The writer knows of no folds within the area which, if referred to sea-level datum, can be classed as domes.

Most of the surface faults in the area are in a trend extending N. 5° E. through the east side of R. 6 E. The individual faults strike N. 35°–40° W., have vertical displacements as much as 140 feet, are generally less than $2\frac{1}{2}$ miles in length, and are *en échelon.* Examples of the surface structure and the fault trend are shown in Figures 8–12.

Since most of the drilling of the Pennsylvanian formations has been by the rotary method, our knowledge of the details of the Pennsylvanian structure below the surface is limited. The unconformity zone at the base of the Pennsylvanian probably represents a peneplain and converges toward the west with the higher members of the Pennsylvanian system (Fig. 7).

PRE-PENNSYLVANIAN STRUCTURE

In general the individual members of the pre-Pennsylvanian formations are nearly parallel, and the structure of the upper part of the Mississippian is the same as that of the sandstones of the Simpson formation. The thickening of the Chattanooga shale toward the south and southwest

[1] "Subsurface Distribution and Correlations of the Pre-Chattanooga ("Wilcox" sand) Series of Northeastern Oklahoma," *Oklahoma Geol. Survey Bull. 40* (1926), p. 16.

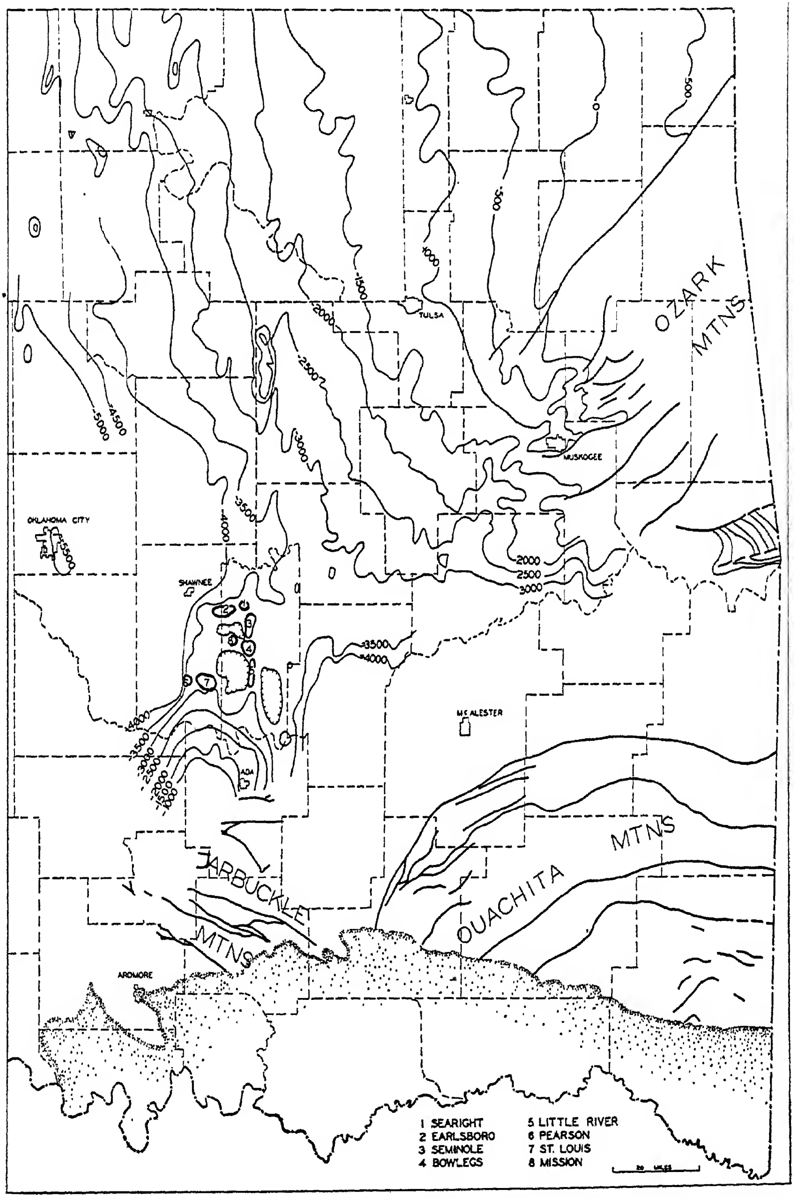


FIG. 7.—Greater Seminole oil fields on regional structure of eastern Oklahoma. Contours on Ordovician, and in part adapted from map published by W. T. Thom, Jr., *Oklahoma Geol. Survey* and *U. S. Geol. Survey*. Contour interval, 500 feet.

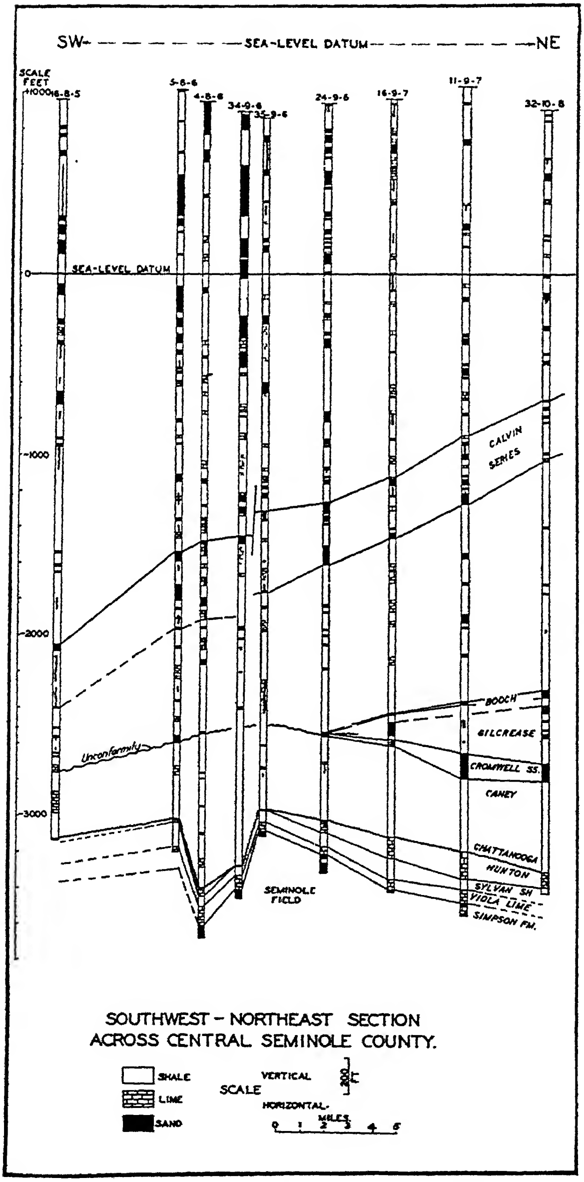


FIG. 8.—Cross section of Seminole County. Logs are referred to sea-level datum and show present structure. From "Geology of Seminole County," *Oklahoma Geol. Survey Bull. 40-BB* (1928).

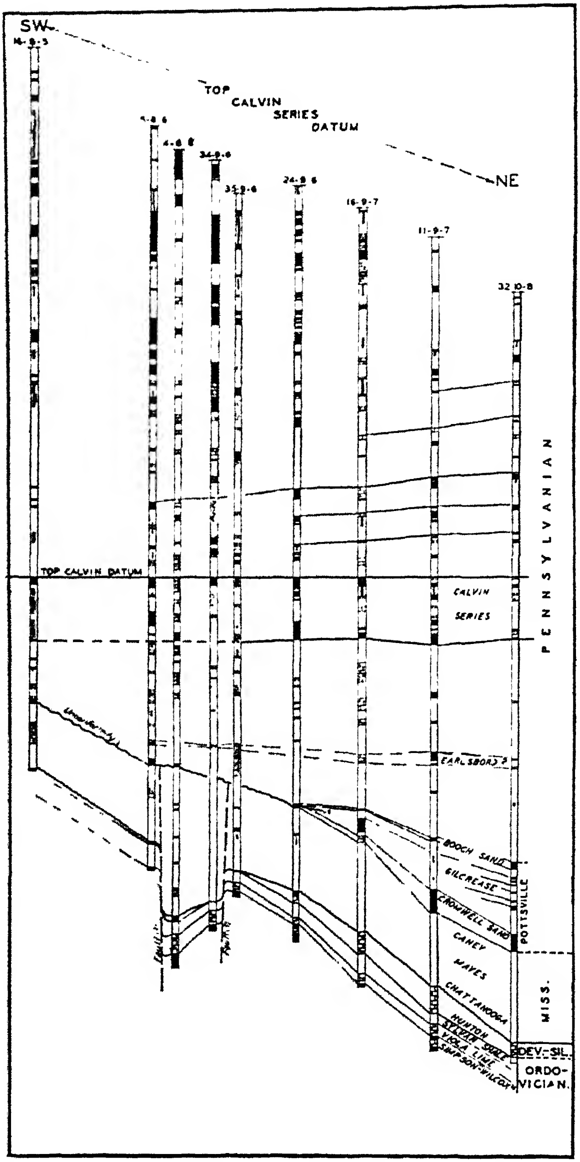


FIG. 9.—Cross section of Seminole County. Logs are referred to top of Calvin series as datum and show structure of older rocks in Calvin time. Same symbols and scale as in Figure 8. From "Geology of Seminole County," *Oklahoma Geol. Survey Bull. 40-BB* (1928).

an overthrust fault or more probably a normal fault cut by a crooked hole.

6. Production in many wells of the irregular areas is different from production in the surrounding wells, while in other irregular areas there is no difference in the characteristics of the production. This suggests that the difference in production of some wells is caused by definite structural irregularities and of others is probably due to crooked holes.

7. It is the writer's opinion that probably 75 per cent of the irregularities are the result of crooked holes and that the other 25 per cent represent true structural irregularities.

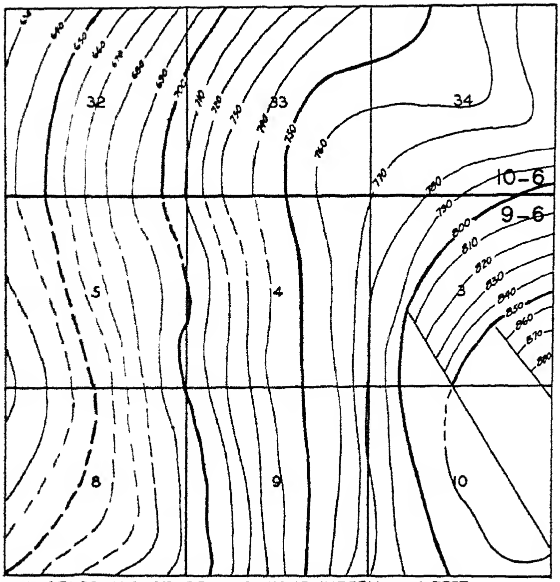
Structure maps of the producing fields are shown in Figures 10–14. For purposes of comparison the map of the surface structure of each of the fields is shown with the map of the structure of the Viola limestone. In each field the difference in structure between the surface and the Viola limestone represents the folding at the end of Hunton time; the faulting and folding in early Pennsylvanian and post-Mississippian time; the normal westward convergence of the Pennsylvanian formations; and the error in depths caused by crooked holes. In each field the broad general outlines of the subsurface structures are shown by the heavy −3,300-foot contour. The low places and irregularities which may be real, or which may seem to exist but are caused by crooked holes, are given less prominence.

These surface structure maps were contributed by the Amerada Petroleum Corporation, the Indian Territory Illuminating Oil Company, and the Gypsy Oil Company; and the subsurface maps are the writer's interpretation of the facts as they are now known.

Figure 15 is a block diagram drawn by J. M. Dale, showing the stratigraphy and structure in the Pearson and St. Louis fields in T. 7 N., R. 3, 4, and 5 E. Attention is called to the thinning of the Hunton limestone over the area of "Wilcox" sand structure and production in Sec. 19, T. 7 N., R. 5 E; the topographic relief of the upper surface of the Hunton limestone, which probably projected nearly 100 feet above the surrounding peneplain; and the pre-Pennsylvanian folding, faulting, and erosion. This area differs from the other fields in that nearly all of the folding and deformation occurred during pre-Chattanooga and pre-Pennsylvanian time.

Figure 16 represents the surface structure on which the location for the discovery well of the St. Louis pool was made. The map is the work of Carl W. Clarke[1] of the Darby Petroleum Company.

[1] Deceased.



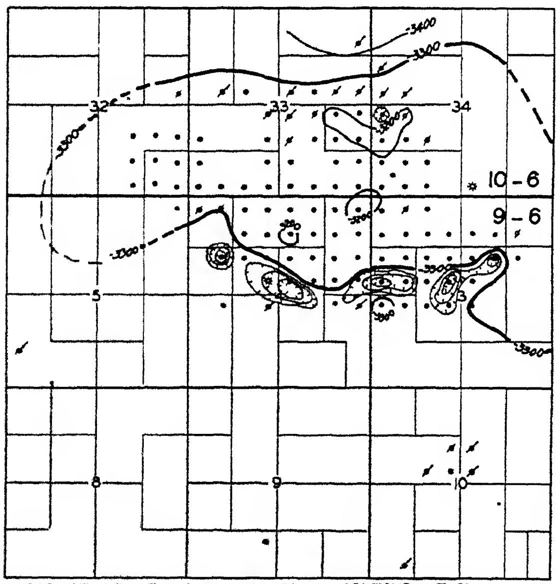


FIG. 10.—Surface and subsurface structure of Searight pool.

OIL-FIELD WATERS

The writer is indebted to L. C. Case of the Gypsy Oil Company for the following data concerning the chemical nature of the waters found in the Hunton lime and the Simpson formation sands of the oil fields.

The Hunton lime, "Seminole" sand, and "Wilcox" sand waters in the Greater Seminole area are similar. The chief difference is the sulphate content which is generally higher in the Hunton lime water. The Earlsboro field, in which the Hunton is generally missing, shows the most characteristic and uniform water analyses of any of the fields. Any of the seven analyses averaged under *C* is very nearly the mean. The Hunton water of the Searight field, averaged under *B*, carries a characteristically high sulphate content but is otherwise very similar to the Seminole sand water. In the Seminole City, Bowlegs, and Little River fields the "Seminole" sand water shows as great differences as those found between the Hunton lime and "Seminole" sand waters.

No difference has been found in the waters of the "Seminole" sand and "Wilcox" sand members which have been

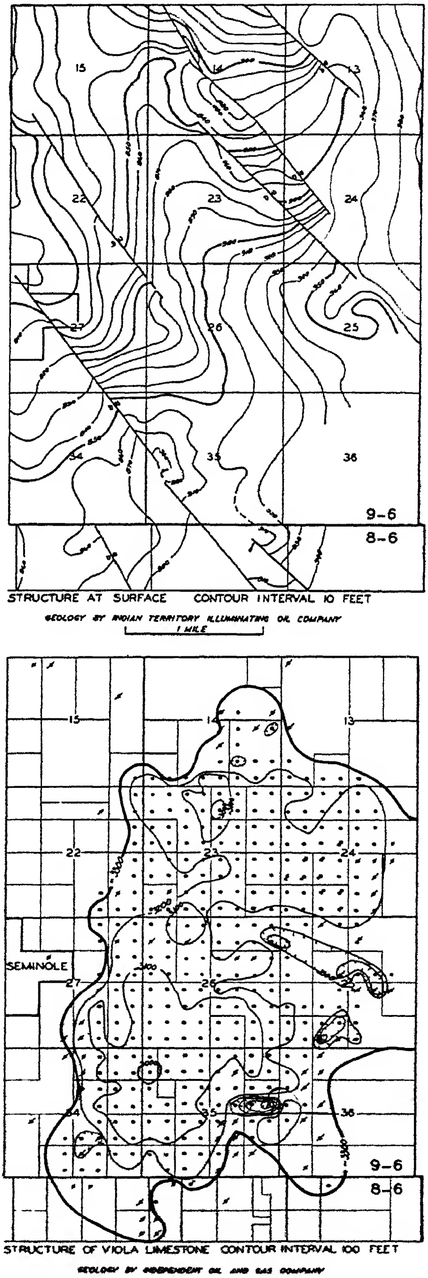
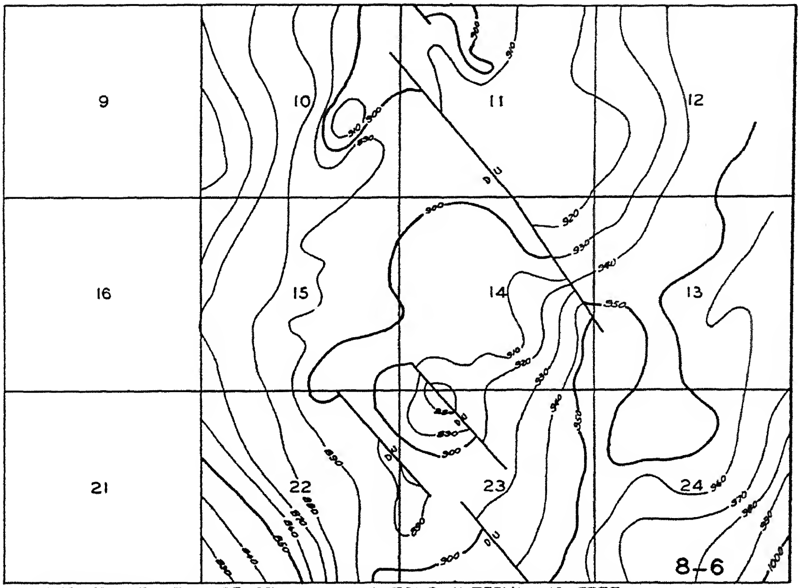
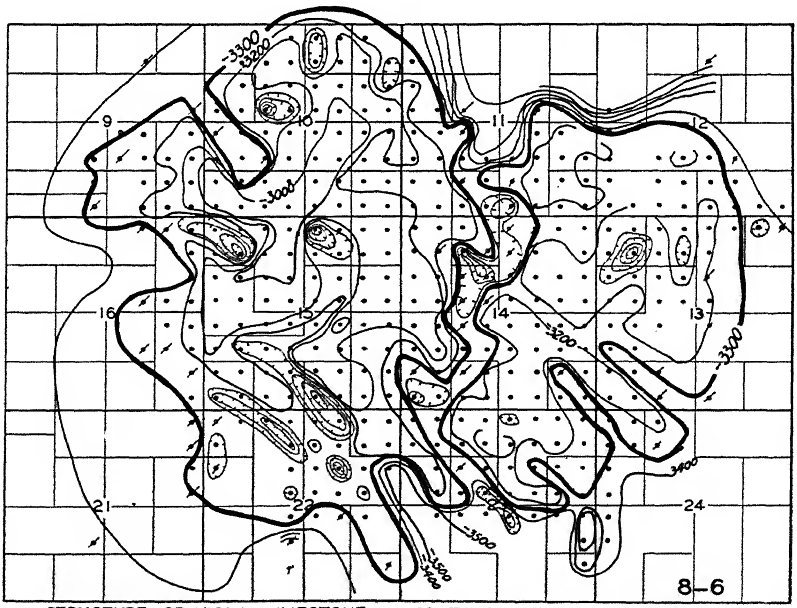


FIG. 11.—Surface and subsurface structure of Seminole pool.



STRUCTURE AT SURFACE CONTOUR INTERVAL 10 FEET
GEOLOGY BY INDIAN TERRITORY ILLUMINATING OIL COMPANY
1 MILE



STRUCTURE OF VIOLA LIMESTONE CONTOUR INTERVAL 100 FEET
GEOLOGY BY INDEPENDENT OIL AND GAS COMPANY

FIG. 13.—Surface and subsurface structure of Bowlegs pool.

analyzed from several wells. In each well the water from the "Seminole" sand was cased off before drilling into the "Wilcox" sand.

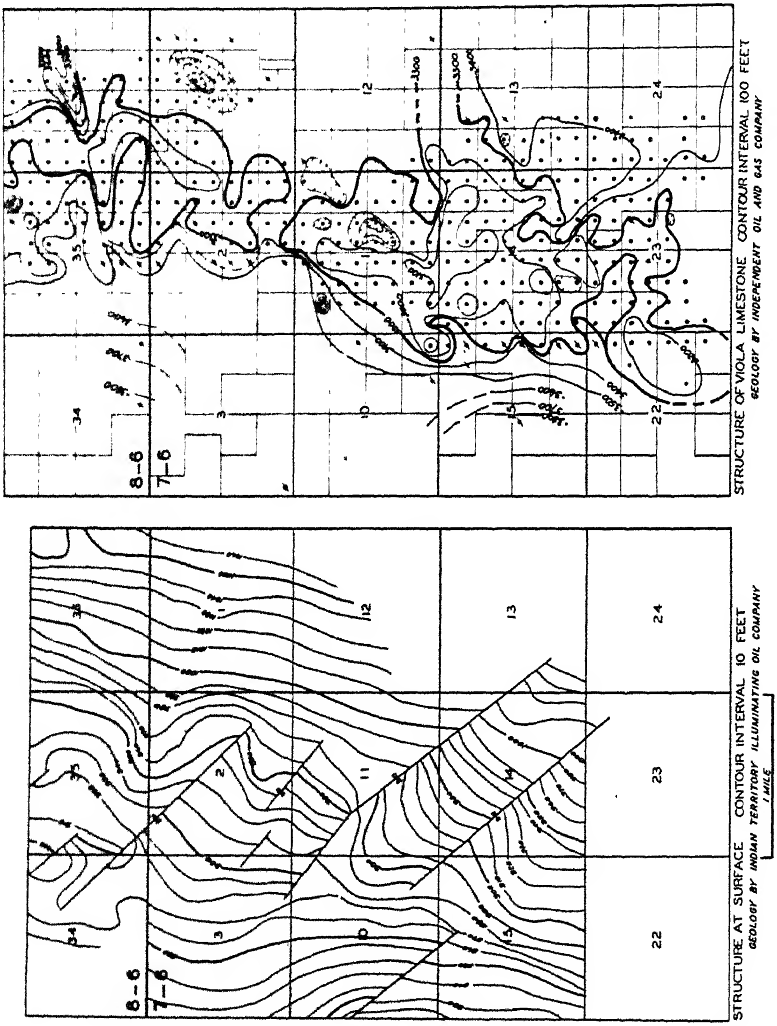


FIG. 14.—Surface and subsurface structure of Little River pool.

Throughout the north half of the county, the water is a typical oil-field brine having a concentration ranging from 150,000 to 170,000 parts per million. A decided dilution of the Simpson formation water occurs south of T. 7 N. This is in the area where wells are commonly reported to

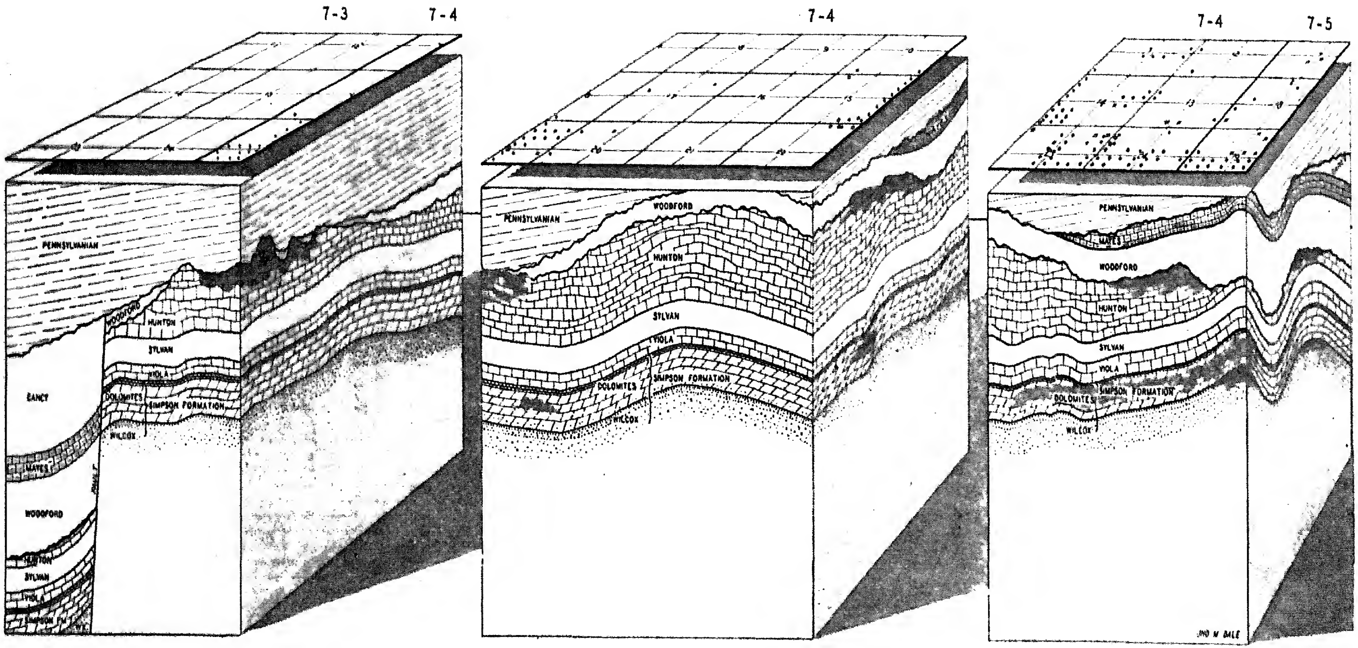


FIG. 15.—Block diagram of Pearson and St. Louis area, T. 7 N., R. 3, 4, and 5 E., Seminole district. Shaded portions of Hunton and Simpson formations indicate position of oil production. Subsequent note.—Later drilling has shown that the "Caney" on the west side of the fault in T.7N., R.3E., is Pennsylvanian.—Editor.

be flowing "sulphur water," but the analyses show no sulphate, or only a trace of it. The odor is caused by hydrogen sulphide gas.

Pennsylvanian waters higher in the geologic section nearer the surface show a progressive decrease in the amounts of sodium, calcium, magnesium, and chloride and an increase in the amount of sulphate. The total concentration also decreases in the shallower sands.

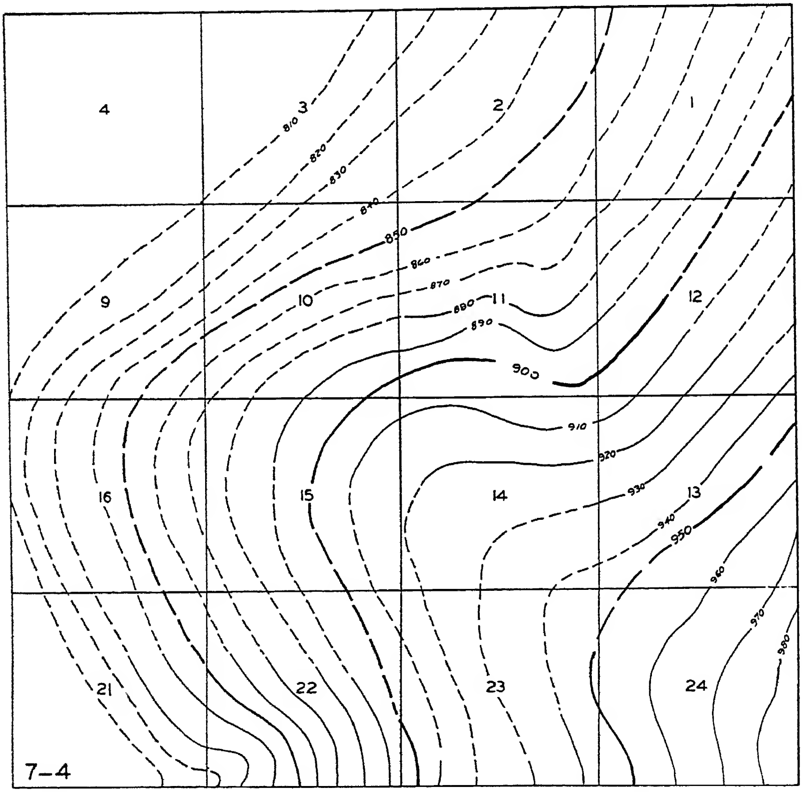


FIG. 16.—Surface structure, St. Louis pool, T. 7 N., R. 4 E. Geology by Carl W. Clarke, Darby Petroleum Company. Width of area, 4 miles.

ANALYSIS OF CRUDE OIL

A. J. Kraemer,[1] of the U. S. Bureau of Mines, summarizes the results of several analyses of Seminole crude oils as follows:

[1] "Analyses of Crude Oils from the Seminole District, Oklahoma," *U. S. Bur. of Mines, Repts. of Investigation, Serial No. 2824* (August, 1927), pp. 2–3.

Although there are a number of producing sands in the Seminole district, it does not seem possible to ascribe definite and distinctive characteristics to the production from any of the sands. The "Wilcox" is the most productive sand in all of the pools in the district. On the basis of the samples that the Bureau of Mines has analyzed (not all of which are included in the report), the gravity of

TABLE IV

AVERAGES OF ANALYSES OF WATERS FROM PRODUCING HORIZONS OF GREATER SEMINOLE DISTRICT*

PARTS PER MILLION

	A	B	C	D
Sodium (Na)......	54,363	49,939	52,097	47,844
Calcium (Ca).....	10,560	7,341	8,460	7,834
Magnesium (Mg)..	2,390	1,540	1,793	1,553
Sulphate (SO_4)....	455	1,022	163	499
Chloride (Cl)......	108,990	93,706	99,379	91,537
Bicarbonate (HCO_3)	43	48	54	52
Total.........	176,801	153,596	161,946	149,319

PERCENTAGE VALUE (PALMER)

	A	B	C	D
Sodium (Na)......	38.31	40.75	39.85	40.24
Calcium (Ca).....	8.54	6.86	7.53	7.39
Magnesium (Mg)..	3.14	2.34	2.62	2.40
Sulphate (SO_4)....	0.15	0.40	0.06	0.16
Chloride (Cl)......	49.84	49.61	49.93	49.80
Bicarbonate (HCO_3)	.01	.02	.01	.01
Total.........	99.99	99.98	100.00	100.00

* *A*, St. Louis field, "Wilcox" sand water, 4,242 feet. Analysis by L. C. Case, Gypsy Oil Company.

B, Searight field, Hunton lime water. Average of two analyses. Analyses by L. C. Case, Gypsy Oil Company.

C, Earlsboro field, "Seminole" sand water. Average of seven analyses. Analyses by L. C. Case, Gypsy Oil Company.

D, Seminole City field, "Seminole" sand water. Average of three analyses. Analyses by L. C. Case, Gypsy Oil Company.

crude oil from the "Wilcox" sand in this district ranges from 37.6° to 43.2° A. P. I., with the average about 40° A. P. I. The sulphur content ranges from 0.25% to 0.43%, with the average about 0.33%. The "gasoline and naphtha" content ranges from 34.1% to 41.3%, with the average about 38.4%. The production from the Hunton lime ranges in gravity between 37.8° and 40.4° A. P. I. with the average about 38.8° A. P. I. The sulphur content ranges from 0.22% to 0.30%, with the average about 0.26%. The "gasoline and naphtha" content of the crude from the Hunton lime ranges from 34.7% to 37.3%, with the average about 36.0%.

DRILLING COSTS

The figures in Table V show the average cost of five wells in different parts of the area, together with the average cost of a dry well and the

TABLE V

AVERAGE COST OF FIVE DEEP WELLS IN SEMINOLE DISTRICT, 1927–28

Rig (122-foot Turnbuckle type)		$ 6,500.00
Slush pit		350.00
Teaming		1,000.00
Drilling contract, 4,200 ft. at $7.50 per ft.		31,500.00
Fuel, oil, water		3,500.00
Tank (250-bbl. wood)		235.00
Cement and cementing		825.00
Pipe:		
50–100 ft. 15½-in. 70 lb.	$ 420.00	
3,900 ft. 8¼ in. 32 lb.	8,035.00	
4,200 ft. 6⅝-in. 24 lb.	6,230.00	
	$14,685.00	$14,685.00
Miscellaneous expense, small pipe, fittings, etc.		1,750.00
Total cost of well to top of "Wilcox" sand		$60,345.00

AVERAGE RECOVERABLE MATERIAL OF A DRY HOLE

8¼-in. casing	$ 3,500.00
6⅝-in. casing	5,000.00
Rig	6,000.00
Tank	200.00
Miscellaneous pipe, fittings, etc.	750.00
Recoverable material	$15,450.00
Average cost of dry hole	$44,895.00

ADDITIONAL EXPENSE ORDINARILY INCURRED WITH A PRODUCING WELL

Separator	$ 1,165.00
Flow line, control head, connections, labor, teaming	500.00
Six 500-bbl. steel vapor-pressure tanks	6,000.00
Air-lift plant complete per well	15,000.00
Additional expense	$22,665.00
Average total cost completed well	$83,010.00

average cost of a producing well. They represent a fair lower average, but a larger expense is the rule due to the many fishing jobs, collapsed pipe, lost hole, and other difficulties encountered in all the fields.

DETAILED STUDIES OF GEOLOGY

An idea of some of the details of the geological problems involved in the Greater Seminole district is contained in the following chapter prepared by Ira H. Cram of The Pure Oil Company. He discusses the information derived from the wells drilled in Sec. 14, T. 8 N., R. 6 E., in the Bowlegs field. Relatively complete sets of well cuttings were kept in this area, and many of the geological problems and irregularities of the entire district are found there. The detailed material presented is to be considered as a "hand specimen" of the Greater Seminole district.

GEOLOGY OF SEC. 14, T. 8 N., R. 6 E.[1]

By Ira H. Cram[2]

INTRODUCTION

Figures 17–22 contain the data on which the following discussion is based. All available drill cuttings from wells of The Pure Oil Company and offsets were examined, and the thickness of the formations sampled are shown in Figures 19–22. Thicknesses of formations were adjusted to the corrected steel-line and cable measurements. Because none of the holes has been surveyed, no corrections in the thicknesses of formations in wells drilled at an angle have been made. The possibility of faulty sampling, the practice of making 10- to 15-foot "runs" in the drilling process, the changes in measurements, and the personal equation which enters into the determination of contacts may cause errors in thicknesses as great as 30 feet. It is believed that these errors are no greater than errors due to the drilling of wells at an angle through formations as thin as those considered in this paper. The accuracy of studying structure by critically examining variations in the stratigraphy is therefore not dependent upon surveys of the holes.

PRODUCTION OF WELLS

A study of the production map (Fig. 17) reveals several important things. Attention is called to the following peculiarities of production as found in Sec. 14, T. 8 N., R. 6 E., which are characteristic of the production in all of the pools of the Seminole area.

1. Of particular significance is the large production of the first completions, the Empire Gas and Fuel Company's Lacy No. 1, the Sinclair Oil and Gas Company's Harjo No. 3 and No. 1, and The Pure Oil Com-

[1] Published by permission of the chief geologist of The Pure Oil Company.

[2] Geologist, The Pure Oil Company, Tulsa, Oklahoma.

pany's Reed No. 1. The wells surrounding these early wells, even though favorably situated structurally, were smaller wells, and most of them did not flow naturally as violently or as long as the earlier wells. The tendency of the first completions to affect the surrounding wells by drainage, or relief of pressure, suggests a direct connection between wells. The wells act as though they have tapped a single large reservoir. If the reservoirs of the Greater Seminole district were cut by as many faults as the subsea elevations seem to indicate, and the fault surfaces were sealed in the ordinary manner, certainly the relief of pressure in one part of the pool would not affect in such a large measure the pressure in another part.

2. Five low producing wells, the producing offsets of which are much higher, are present in Section 14. They are The Texas Company's Reed No. 9 and No. 13, the Empire Gas and Fuel Company's Lacy No. 5 and No. 6, and The Pure Oil Company's Reed No. 20. No evidence of faulting or sharp folding in these wells has come to the writer's attention; they may, therefore, be simply crooked holes.

3. The possibility that impurities in the sand affect the localization of petroleum is demonstrated by a study of The Pure Oil Company's Reed No. 14. This well, though very low and a late completion, had a very shaly sand body which may partly explain the poor production.

4. The Carter Oil Company's Harjoche No. 8 is an example of a dry hole evidently as high structurally as offsetting producers. This condition may be due to drainage, to poor porosity of the sand, or to structure. If structure is the cause, it may be assumed that Harjoche No. 8 is a straight hole and the offsetting producers crooked holes.

5. The Sinclair Oil and Gas Company's Harjo No. 4 is an example of a low dry hole surrounded by large producers of higher subsurface elevation. Again drainage or sand conditions may partly account for the condition. If the subsea elevations of Harjo No. 4 and surrounding wells express the true structural relations, there is the problem of explaining a structural depression of so great a depth covering so small an area. If only Harjo No. 4 were a crooked hole, and, as a result, the well were no lower than the offsets, it would be in the same category as Harjoche No. 8, a high dry hole. Conclusive evidence explaining either phenomenon is lacking.

6. Areas of low dry holes surrounded by producing wells, such as the north-central part of Section 14, are found in several places in the Greater Seminole district. This particular dry area is partly due to faulting and is more fully discussed in the following paragraphs.

THICKNESSES OF FORMATIONS

Faulting, folding, and intraformational erosion affect the thicknesses of formations found in wells. Thicknesses, therefore, are to be studied if the true structure and structural history are to be learned.

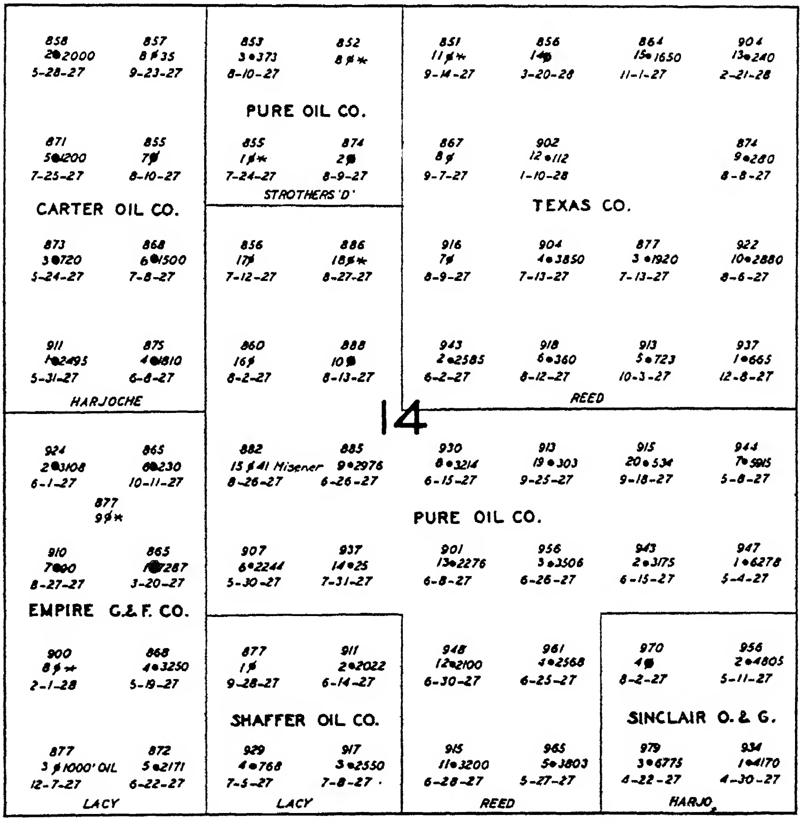


Fig. 17.—Production map of Sec. 14, T. 8 N., R. 6 E., with well number at left of wells, elevation in feet above, maximum daily production in barrels at right, and date of completion below. Starred wells were abandoned before reaching the sand. Wells with circle were drilled to the second sand. The well with two circles had a hole full of water in the second sand. Width of area, 1 mile.

The stratigraphy of Section 14 is that of the Bowlegs pool shown on Figure 3. Little is known of any local variations in the thicknesses of the Pennsylvanian beds because most of the cuttings were available only from the lower Caney and older formations. A considerable section of Pennsyl-

vanian was available for study from the Shaffer Oil Company's Lacy No. 1, The Pure Oil Company's Strother "D" No. 1, and Reed No. 18. The stratigraphy corresponds fairly well with that shown on the type section (Fig. 3). The thin limestone in the basal "Boggy" is present in the same

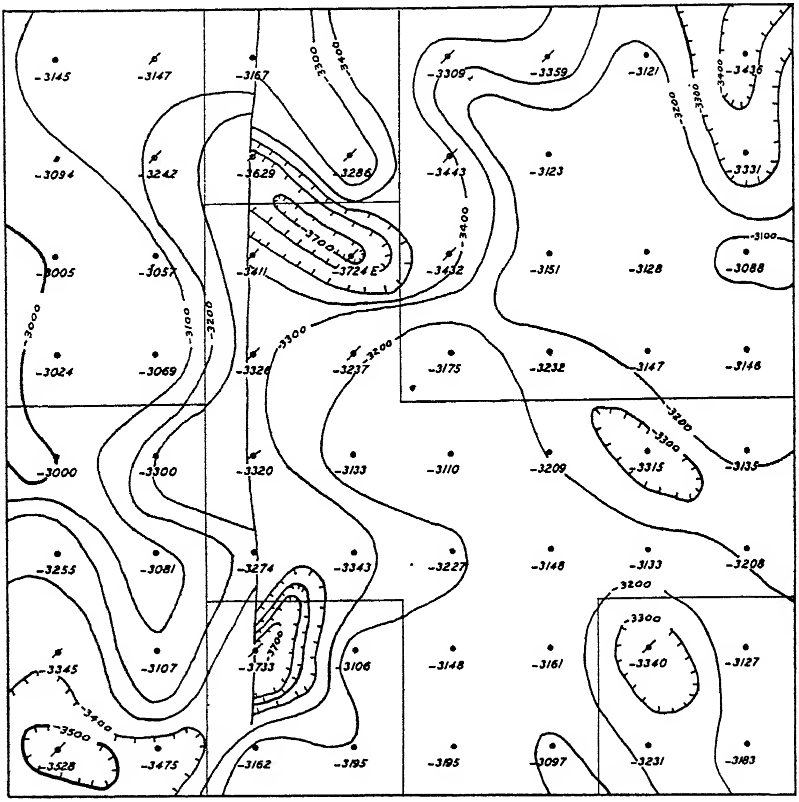


FIG. 18.—Structure of Viola limestone, Sec. 14, T. 8 N., R. 6 E. Contour interval, 100 feet. Width of area, 1 mile. No corrections have been made for deviations of holes from the vertical. Crooked holes may account for many of the irregularities.

position in Lacy No. 1. This thin limestone and the underlying sand and shale zone are persistently present at the base of the Pennsylvanian throughout the pools of Ranges 5 and 6 of the Greater Seminole district. In the Little River pool this zone overlies the Wapanucka limestone or Cromwell sand, but in the other pools of Ranges 5 and 6 the Wapanucka and Cromwell are absent, and the previously-mentioned sandy shale zone

overlies the Caney shale of Mississippian age. There is a possibility that some of the Caney below the Cromwell sand is Pennsylvanian in age, especially in the southern part of the Greater Seminole district. However, any Pennsylvanian Caney present is very thin, and for all practical purposes the top of the Caney in the Seminole area is the top of the Mississippian. The thin limestone seems to be basal Boggy in age; and for

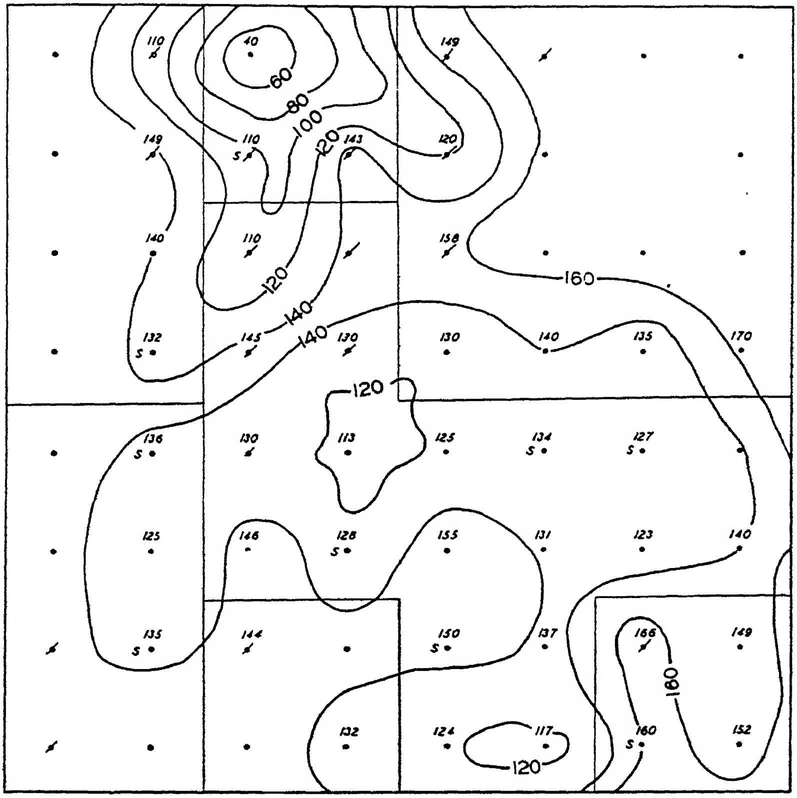


FIG. 19.—Thickness of Woodford shale, Sec. 14, T. 8 N., R. 6 E. *S* indicates presence of Sycamore limestone. Contour interval, 20 feet. Width of area, 1 mile.

the sake of simplicity the underlying shale and sand zone is also referred to the Boggy formation, although it is realized that it may contain fringes of any formation found in the normal sequence between the Wapanucka and the Boggy. This basal sand and shale zone is not lithologically the same throughout the Seminole area. In many places it contains beds of conglomerate. In Strother "D" No. 1 and in Lacy No. 1 it was

mostly detrital sand, but in Reed No. 18 it was sandy shale. The remarkably regular interval between the thin limestone of the "Boggy" and the top of the Caney throughout the area north and west of the Little River pool is direct evidence that the Mississippian surface was essentially flat when the "Boggy" sea advanced. Except for a local slight thickening of

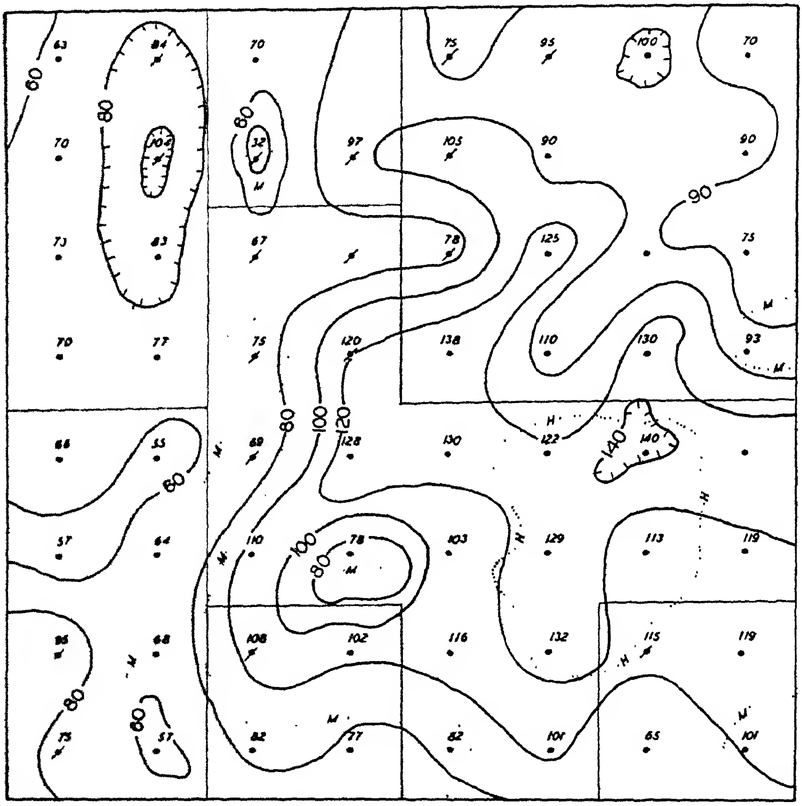


FIG. 20.—Thickness of Sylvan shale, Sec. 14, T. 8 N., R. 6 E. *H* indicates distribution of Hunton; *M* indicates distribution of Misener. Contour interval, 20 feet. Width of area, 1 mile.

the conglomerate and sandy shale zone at the base of the "Boggy," no evidence has come to the writer's attention that indicates any amount of filling of basins in the old erosion surface.

In Lacy No. 1 the Caney is only 298 feet thick, much thinner than any section of Caney found by the writer in the Bowlegs or Seminole

City pools; yet the stratigraphy of the basal "Boggy" is entirely normal, precluding the possibility of any amount of filling of an old topographic basin. Inasmuch as there is unmistakable evidence of faulting below the Sylvan shale in Lacy No. 1, the abnormally thin Caney section is believed to be the result of the well crossing a fault in the Caney. Instead of the normal sequence of beds between the Sylvan and Simpson sand, there is in this well a most irregular succession of Sylvan shale, Viola limestone, and "Simpson" limestone, dolomitic limestone, and silicified sand, decidedly suggestive of a crushed zone due to faulting. Certainly no one familiar with the extreme regularity of the Viola and Simpson sections could possibly attribute this heterogeneous section to lateral gradation.

The thickness of the basal bed of the Caney known as the "Mayes" limestone has been taken into account in the present project, but no map of its thickness was constructed. The "Mayes" is merely a limy zone in the base of the Caney, and grades into the Caney shale member of the Caney. It may, therefore, vary in thickness due to this gradational contact. Nevertheless, the "Mayes" is remarkably persistent in thickness in those wells examined by the writer, except in The Pure Oil Company's Strother "D" No. 3, in which well the "Mayes" is only 60 feet thick instead of the normal 100 feet. This discrepancy in thickness is due to faulting and is more fully discussed in the following paragraphs.

In the Bowlegs pool the Woodford shale is a remarkably uniform bed of black shale, in most places differing not more than 20 or 30 feet from an average of 140 feet. Figure 19 shows this tendency with one important exception, the 40-foot section in Strother "D" No. 3. This thin section is attributed to faulting. It can scarcely be due to post-Woodford or pre-Woodford erosion. If due to pre-Woodford erosion, the thickness of the Woodford and Sylvan would tend to compensate; but Figure 21 shows conclusively that such is not the case. In fact the close similarity of the contour pattern of Figure 19 and Figure 21 is decidedly suggestive that the Woodford sea spread over the flat surface of the Sylvan shale, Hunton limestone, and Misener sand. Although there is a stratigraphic break between the Woodford (Kinderhook) and "Mayes" (Chester)[1] equivalent to the entire Osage and Meramec groups of the Mississippian, it is believed that little erosion occurred at that time. The preservation of patches of

[1] The "Mayes" limestone of the Greater Seminole district is generally considered the equivalent of the Mayes formation of northeastern Oklahoma correlated as Chester by L. C. Snider (Oklahoma Geol. Survey Bull. 24). The Chester age of the Mayes is not beyond question, and it has not yet been proved that the "Mayes" of the Seminole area is the true Mayes.

the Sycamore limestone of upper Kinderhook age in nine of the wells is cited as evidence (Fig. 19). Pre-Chester erosion was unable completely to remove such a thin deposit as the Sycamore limestone, and is believed, therefore, to have been too feeble to have removed any considerable amount of the Woodford. If, then, the Woodford sea spread over a rela-

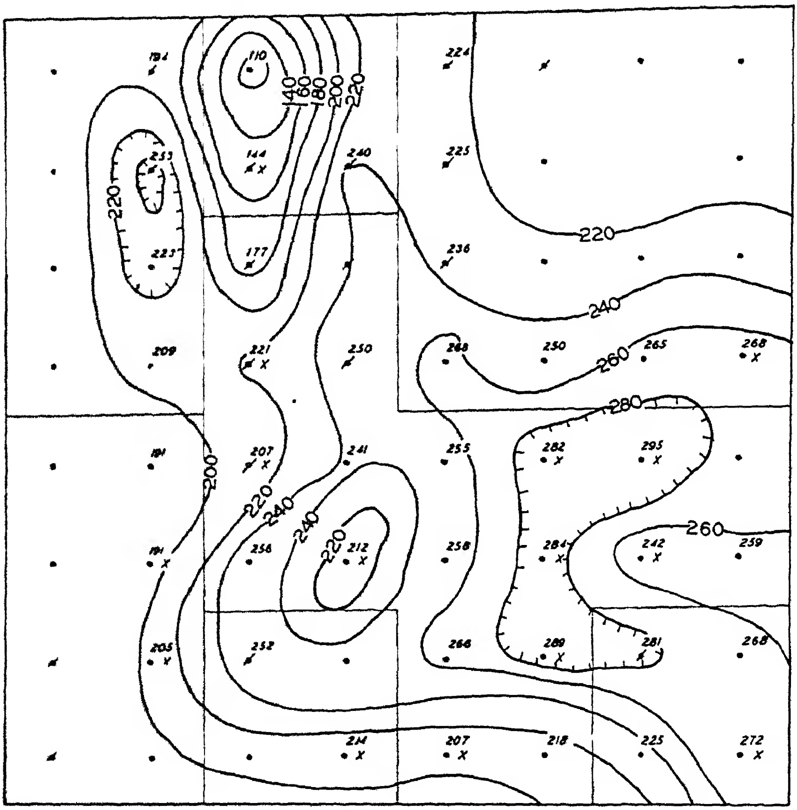


FIG. 21.—Thickness of interval from top of Viola limestone to top of Woodford shale, Sec. 14, T. 8 N., R. 6 E. *X* indicates presence of Hunton or Misener. Contour interval, 20 feet. Width of area, 1 mile.

tively flat surface, and the top of the Woodford was not subjected to any intense erosion, abnormally thin or thick sections of Woodford are probably due to deformation of the strata. If the dominant form of deformation were intense folding, greatly increased thicknesses of Woodford ought to be found associated with squeezed sections only 40 fee

in thickness. The former have not been found. Indeed, in the Greater Seminole district where thicknesses of pre-Pennsylvanian formations are found that differ greatly from the normal for that particular area, these thicknesses are almost invariably greatly decreased rather than increased. And this is in spite of the crooked holes which increase the seeming thicknesses. These facts lead to the inference that faulting rather than intense folding is the dominant form of local deformation within the large dome folds. Surely the evidence afforded by the thin "Mayes" and Woodford sections in Strother "D" No. 3 indicates that the drill passed through the fault surface into the upthrown side after having penetrated 60 feet of "Mayes."

Although as shown in Figure 20 the Sylvan may vary considerably in thickness due to post-Devonian uplift, warping, and subsequent erosion, the very thin section, only 32 feet, in Strother "D" No. 1 is suggestive of abnormal conditions. "Simpson" dolomite and silicified sand were encountered directly below the Sylvan and were penetrated 5 feet. The Simpson limestones and dolomitic limestones above the "Seminole" sand vary in thickness due to gradation into the underlying "Seminole" sand and due to late Ordovician erosion. The Viola (Fernvale) varies in thickness due to its deposition upon a somewhat irregular "Simpson" surface, and also possibly to a slight erosion interval following its deposition. The absence of the Viola in any section where the Sylvan overlies it is so rare as to demand special attention. The map (Fig. 22) shows a fairly regular thickness for the Viola except in Strother "D" No. 1 and in Lacy No. 1. Although it is theoretically possible to interpret the conditions in Strother "D" No. 1 as due to erosion, the extreme persistence of the Viola throughout the Seminole area, the absence of the Viola and probably much of the "Simpson" in this well, the thin Sylvan section, and the evidence of faulting in Strother "D" No. 3 and Lacy No. 1 are strongly indicative of faulting as the cause of the irregular stratigraphic sequence.

The three wells containing the evidence of faulting are in a line of low wells extending northward into Sec. 11, T. 8 N., R. 6 E. In Section 14 five of the wells in this line are dry holes, and two (and these are the highest wells) are oil wells. The west offsets of these wells are all higher wells and, with the exception of two, oil wells. Surely such an alignment suggests faulting; this and other evidence in three wells indicate that a fault exists separating the line of relatively high wells from the line of relatively low wells. According to the writer's interpretation Strother "D" No. 3 drilled through the fault surface, Strother "D" No. 1 drilled through or into the fault surface, Reed Nos. 15, 16, and 17 drilled into the down-

The Texas Company's Reed No. 7 is at the south end of a line of low dry holes extending northward into Section 11. The east offsets to these wells are, with one exception, higher wells and producers. Again faulting is suggested, but here no stratigraphic evidence has come to the writer's attention. The map shown in Figure 18, therefore, is contoured without a fault in this position. This map, though undoubtedly as inaccurate as the depths of the holes, represents in a degree the true structure.

SUMMARY

The combined evidence furnished by the stratigraphy, production, and, to some extent, subsea elevations gives a picture of a relatively gentle fold faulted in one place, resulting in an area of dry holes in the depression east of the fault which area divides the north half of Section 14 into two producing areas. The evidence presented is insufficient to explain the low areas outside of the area affected by the fault. Possibly it is not too much to expect that a dome as large as the Bowlegs dome would have some down-warped spots such as the area into which Harjo No. 4 was drilled. Conclusive evidence as to the structural position of these irregularities is absent.

It is believed that the method of attack used in studying the structure of Sec. 14, T. 8 N., R. 6 E., if used throughout the Seminole area, would throw considerable light upon the structural conditions. The holes will continue to be crooked and the subsurface elevations, therefore, useless unless corrected by surveys of the holes; but the thicknesses of the beds are ordinarily available, and should be used, especially in those areas where faulting is suspected. The geologic history of the Greater Seminole district is the same as the history of Sec. 14, T. 8 N., R. 6 E.; therefore, any reasoning used in this paper is directly applicable to the study of similar problems at any place in the Seminole area.

DELAWARE EXTENSION POOL, NOWATA COUNTY, OKLAHOMA[1]

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ABSTRACT

The Delaware Extension pool is a long, narrow sand lens projecting westerly from the north end of the Nowata pool, Nowata County, Oklahoma. The pool was drilled up in 1910 and 1911 and has produced to date approximately 4,000,000 barrels of oil gross. The oil comes from the Bartlesville sand at a depth of 800 feet on the east end and 1,200 feet on the west end. Geologically the pool is entirely a sand-lens condition and is productive regardless of local structure. The conditions suggest that the sand lens is a buried river channel with similarities to the east-west shoestring pools of Kansas.

The Delaware Extension pool is in Nowata County, Oklahoma. The pool was discovered in 1909 and was drilled up in 1910 and 1911. Production is obtained from a sand at the Bartlesville horizon which has a maximum thickness of 70 feet and an average thickness of approximately 40 feet. The wells range in depth from 800 feet on the east end to 1,200 feet on the west end. Initial production in the several parts of the pool was large, several wells coming in with productions of more than 1,000 barrels. Nearly 900 producing wells were drilled in the pool. It is estimated that they have produced 4,000,000 barrels gross, a recovery of approximately 1,000 barrels per acre.

The Delaware Extension pool is a west extension of the Nowata-Chelsea pool at its north end. The subsurface structure is shown in the accompanying map (Fig. 1), the production being outlined by the broken lines. The pool is a lens of sand at the Bartlesville sand horizon, which crosses several structural features that do not seem to have influenced the accumulation of oil and gas. From east to west the top of the sand drops in 7 miles from 100 feet to 300 feet below sea-level. On the north and south sides of the pool, the sand pinches out. On the west end the sand lens becomes narrower and spotted. There are several discontinuous spots of production west of the area shown.

[1] Presented by title before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, June 1, 1928.

[2] Petroleum engineer, Dunn and Lewis, Commercial Building.

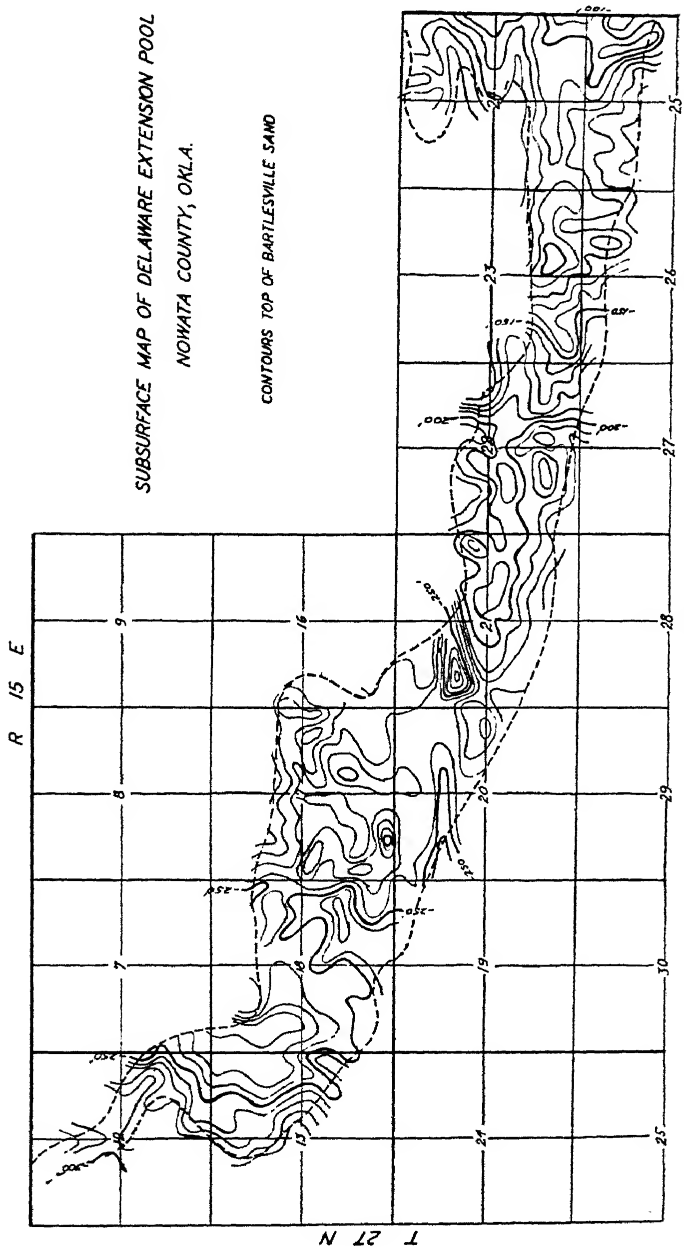

FIG. 1.—Subsurface structure of Delaware Extension pool, Nowata County, Oklahoma, contoured on top of Bartlesville sand. Contour interval, 10 feet. Length of area mapped, 7 miles.

DEPEW AREA, CREEK COUNTY, OKLAHOMA[1]

HELEN M. MARTIN[2]
Tulsa, Oklahoma

ABSTRACT

The Depew area of Creek County, Oklahoma, is southwest of Bristow and includes two small pools and scattered clusters of wells. Surface structure is mapped with some difficulty owing to the fact that the sandstones and shales have weathered to a heavy soil cover with few and widely separated rock exposures. The eastern half of the area shows uniform westward dip, but the western half is broken by a series of *en échelon* faults with two small anticlines in Sections 8, 9, and 16. Subsurface structure in the Poor Farm and Depew fields shows small, gently dipping anticlines with the main axis north-south. Subsurface structures mapped on the Hogshooter lime, the Checkerboard lime, the base of the Layton sand, the base of the Bartlesville sand, and the top of the "Wilcox" sand, vary but little, but show a westward shifting of the axis of the fold. Production in the area is from the Layton, Cleveland, Prue, Dutcher, and "Wilcox" sands.

The part of the Depew area under discussion is southwest of Bristow, in T. 15 N., R. 8 E., Creek County, Oklahoma. It is named from the village of Depew in the northwest corner of the township.

In the township are two well-developed pools, the Poor Farm pool in Sec. 35, T. 16 N., R. 8 E., and Secs. 2 and 3, T. 15 N., R. 8 E., and the Depew pool in Secs. 5, 8, 9, 17, and 18, T. 15 N., R. 8 E. Between these pools, another small pool is being developed in Sections 10 and 15. Other small pools are in the southwestern part of Section 15 and in Section 30; clusters of wells are scattered throughout the township, notably in Sections 23 and 26. The Sheetz pool of T. 14 N., R. 8 E., extends into the southern part of the township.

SURFACE STRATIGRAPHY

The area is mapped by the United States Geological Survey in the southwest corner of the Bristow Quadrangle. The surface geology has been discussed by Fath in the United States Geological Survey report on that quadrangle[3] from which the following résumé of surface conditions is largely taken. The rocks exposed at the surface are all sandstone and

[1] Manuscript received by the editor, April 8, 1928.

[2] The Carter Oil Company.

[3] A. E. Fath, "Geology of the Bristow Quadrangle, Creek County, Oklahoma," *U. S. Geol. Survey Bull. 759*, pp. 44–52.

shale, with a few non-persistent limy beds of the Bristow formation of Pennsylvanian age. The sandstones are soft and friable and of different shades of brown. They have weathered to a loose rock and soil cover with a few widely separated exposures, which makes the area difficult to map geologically. The exposed beds are massive sandstones lithologically so similar that it is difficult to differentiate them. Also, the beds vary in thickness and in places change abruptly from sandstone to shale.

In Section 11 and the eastern part of Section 10, Township 15 North, Range 8 East, a very abrupt change from sandstone to shale is well illustrated. Here a sandstone bed, which to the south appears to be persistent and to have a thickness of 30 feet or more, changes toward the north into red shale. This change is best seen in the first valley east of the west quarter corner of Section 11, where it takes place within a distance of 100 yards. It is not merely a local change but appears to persist along an east-west line as far as the bed is exposed.[1]

The shales, where exposed, are the red shales of the Bristow formation, but they are largely covered by the sands weathered from the sandstone outcrops.

SUBSURFACE STRATIGRAPHY

Subsurface correlations are made with little difficulty (Fig. 1). The base of the Bristow formation is found at depths ranging from 550 to 700 feet. Below the basal sandstone of the Bristow formation, the Tiger Creek sandstone, is the upper shale member of the Copan formation, which, with all five[2] members represented, rests on the Hogshooter (Layton) lime at depths ranging from 1,150 to 1,275 feet. The Hogshooter lime, 10–20 feet thick, is the top of the Coffeyville formation, whose thickness ranges from 450 to 500 feet. In the Depew area, the Layton sand is generally about 150 feet below the Hogshooter lime and is separated from the Checkerboard lime, which is near the base of the formation, by a 200-foot shale interval.

In some places immediately below the Checkerboard lime, in others separated from it by a thin shale interval, is the Cleveland sand near the top of the Broken Arrow formation. This formation is ordinarily 750 feet thick and is logged as blue and gray shales with occasional limestone beds. Below the Broken Arrow formation and above the Cherokee shales is a zone ranging from 100 feet to 150 feet in thickness, consisting of three thin limestones and interbedded blue, gray, and black shales—the Fort Scott limestone. In the southeastern part of the area, a sand body, Prue sand, is below the Fort Scott and is productive. In a few wells, another

[1] A. E. Fath, *op. cit.*, p. 9.

[2] A. E. Fath, *op. cit.*

sand (Peru?) is recorded below the uppermost of the three thin limestones; in a few others, the "Wheeler" sand is logged within the zone.

Below the Fort Scott is a dark shale ranging from 750 to 900 feet in thickness. This interval may be all Cherokee shale or may be Cherokee

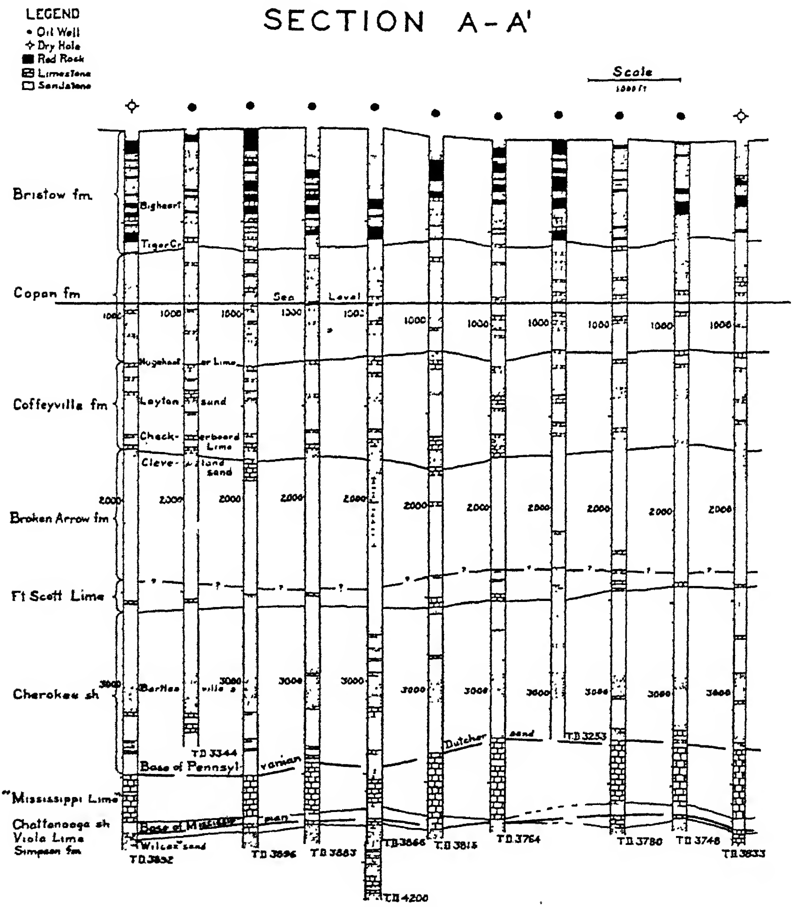

FIG. 1.—Cross section *A-A'* eastward across Depew fold, as shown by well logs. For location, see Figure 3. Depths in feet.

with a thin section of shale of Mississippian age near the base. The Bartlesville (Glenn) sand, ranging from 75 to 100 feet, with the thin, hard, unnamed lime at its base, is about 400 feet below the top of the Cherokee shales. Below the Cherokee and lying directly on the "Mississippi lime,"

or separated from it by a thin black shale, is the Dutcher sand. The Dutcher is locally absent in the area or so thin that it is not logged by the drillers. The "Mississippi lime" ranges from 230 to 375 feet in thickness (Fig. 7). Below the "Mississippi lime" is 20–60 feet of black Chattanooga shale overlying 20–40 feet of Viola lime, below which is the "Wilcox" sand reached at depths ranging from 3,690 to 3,920 feet. One well, the Wolverine Petroleum Company's M. E. Wilson No. 7 in the NW. $\frac{1}{4}$, NE. $\frac{1}{4}$, NW. $\frac{1}{4}$, Sec. 17, drilled into the Simpson formation to a depth of 4,200 feet, finding interbedded green, blue, and black shales, pink, gray, and white limestones, and brown and white sands; but with no oil showings below the upper or "Wilcox" sand. In a few off-structure wells, not more than 30 feet of white shale, the Sylvan, is reported below the Chattanooga.

STRUCTURE

The description of the general structural features of the Bristow quadrangle is also a description of the Depew area. The area is on the regional monocline of northeastern Oklahoma. The rocks strike about N. 15° E., and dip northwest from 60 to 75 feet per mile. In the eastern part of the area, the western monoclinal dip is uniform. No change of dip or surface structure indicates subsurface structure of the Poor Farm pool, but in the western part the uniform dip is interrupted by a series of *en échelon* faults. The group trends north-northeast, but the trend of the individual faults is northwest at an angle of about 45° to the fault zone. Associated with the faults are two small anticlinal folds, a north-northwest-pitching fold in Sections 8 and 9 and a small closed fold along the west side of Section 16[1] (Fig. 2).

The subsurface structure, as determined by well-log information, shows the Poor Farm pool, the Depew pool, and the small pool between them to be small anticlinal folds with less than 100 feet of closure, the longer axis extending north and south. The Poor Farm anticline is about $1\frac{1}{2}$ miles long and $\frac{1}{2}$ mile wide, and the Depew anticline is nearly $2\frac{3}{4}$ miles long and ranges from $\frac{1}{2}$ mile to $1\frac{1}{4}$ miles in width. As before stated, no surface structure indicates the Poor Farm pool, but the Depew pool underlies the zone of *en échelon* faults in the western part of the township. Subsurface structures for the Depew pool have been mapped on the top of the Copan formation, on the Hogshooter lime (Fig. 3), the Layton sand, the Checkerboard lime, the top and base of the Bartlesville sand (Fig. 4), the Dutcher sand (Fig. 5), and the "Wilcox" sand (Fig. 6). The structure on the top of the Copan (base of Tiger Creek sandstone) conforms rather

[1] A. E. Fath, *op. cit.*

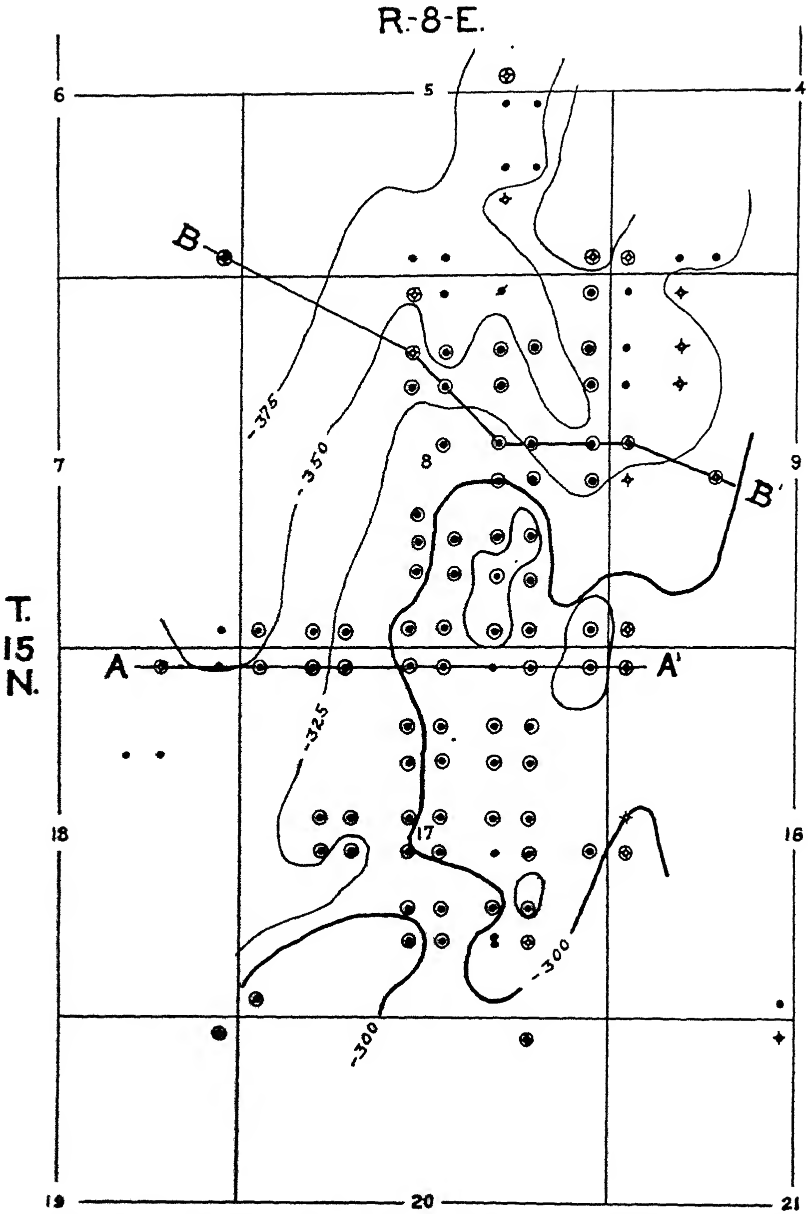

FIG. 3.—Subsurface contour map on top of Hogshooter limestone, below sea-level. Contour interval, 25 feet. Width of area mapped, 2 miles.

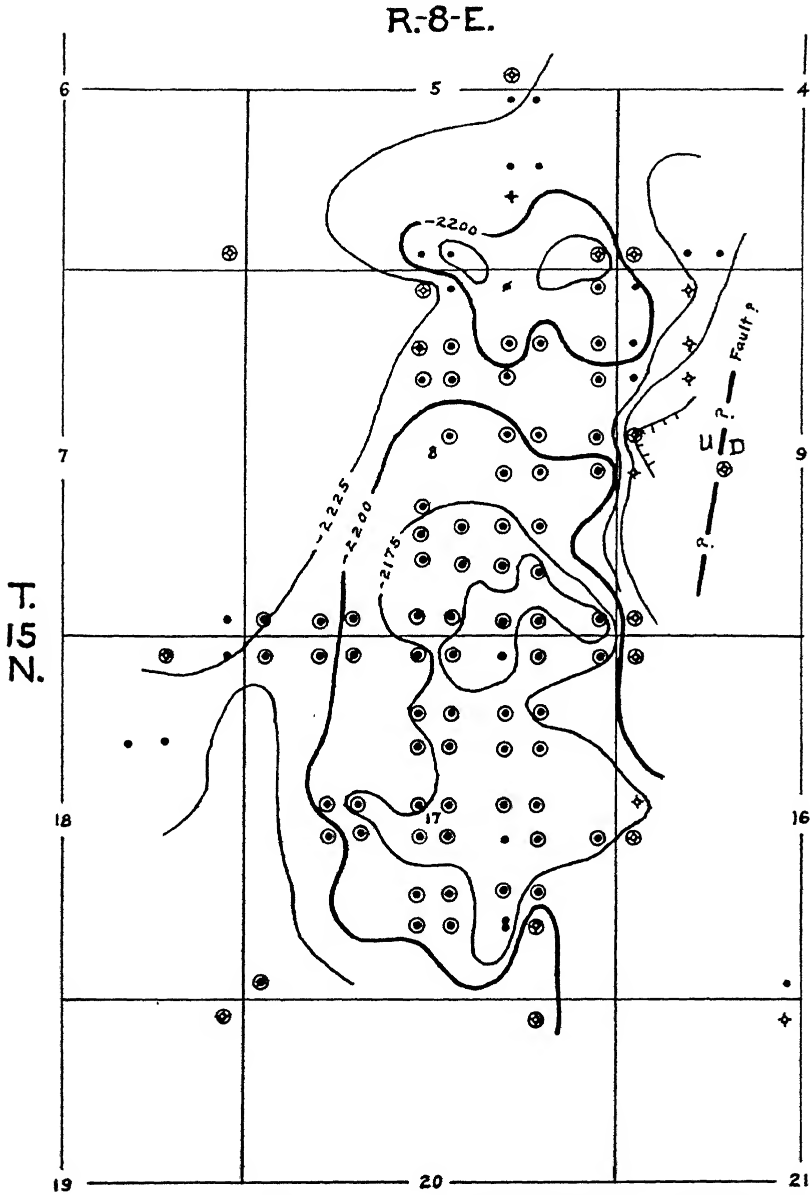

FIG. 4.—Subsurface contour map on base of Bartlesville sand, below sea-level. Contour interval, 25 feet. Width of area mapped, 2 miles.

However, a change in the attitude of the strata below the Oswego–Fort Scott zone is evident (Figs. 5 and 6); the dip along the east side of the fold is more pronounced and indicates a possible fault. The writer is of the opinion that the Depew fold is terminated on the east in the lower formations by a westward-dipping reversed fault with a high angle of dip and downthrow on the east (Fig. 7), which grades upward into the small fold shown in the upper formations and at the surface in the SW. $\frac{1}{4}$ of Section 9. Probably faults in the lower strata, rather than narrow synclines, separate the Poor Farm and Depew folds from the fold between them.

Some evidence may be adduced that the dry hole in the NW. $\frac{1}{4}$, NE. $\frac{1}{4}$, SW. $\frac{1}{4}$, Sec. 9, drilled almost on the crest of the fold mapped by Fath (Fig. 2), passes through the fault. The log, if correct, may be interpreted as having a repetition of the Bartlesville sand zone (thick sand body and thin lime below it) from 2,892 to 3,060 feet and from 3,278 to 3,480 feet, and no Dutcher recorded, as in many other wells of the field. The well would then cross the fault about 3,270 feet below sea-level, which would give a vertical throw ranging from 380 to 400 feet. The thinner section of "Mississippi lime," as compared with the thickness of the lime on the fold, is considered as evidence of earlier faulting, producing a line of weakness. The log of the dry hole in the NE. $\frac{1}{4}$ of Section 9 offers similar evidence of faulting. Or, the fault may be between the edge of the pool and the dry hole and may have occurred before the deposition of the Dutcher sand; thus, the thick sand body between 3,278 and 3,480 feet may be Dutcher deposited in the trough of the fault block.

In either condition the fault does not extend to the Fort Scott horizon, as the Fort Scott and beds above it show no evidence of a north-south fault. Unfortunately, the lack of samples from the well prevents proof or disproof of either hypothesis. Evidence from the logs of a well or two is recognized as being far from conclusive but it is offered for what it may be worth. The Poor Farm pool offers little evidence for speculation about possible buried faults, and too little is yet known about the fold between the Poor Farm and Depew folds, although it is evident that a fault exists between the wells in the SE. $\frac{1}{4}$, SW. $\frac{1}{4}$, Sec. 3, and NE. $\frac{1}{4}$, NW. $\frac{1}{4}$, Sec. 10, and their east offset wells. Accumulation in the Dutcher and "Wilcox" sands is evidently due to some pre-Fort Scott warping and faulting of the older beds.

DEVELOPMENT

Development commenced in the area in 1912, when a well was drilled in Sec. 2, T. 15 N., R. 8 E., by the Kahawna Oil Company. The well was

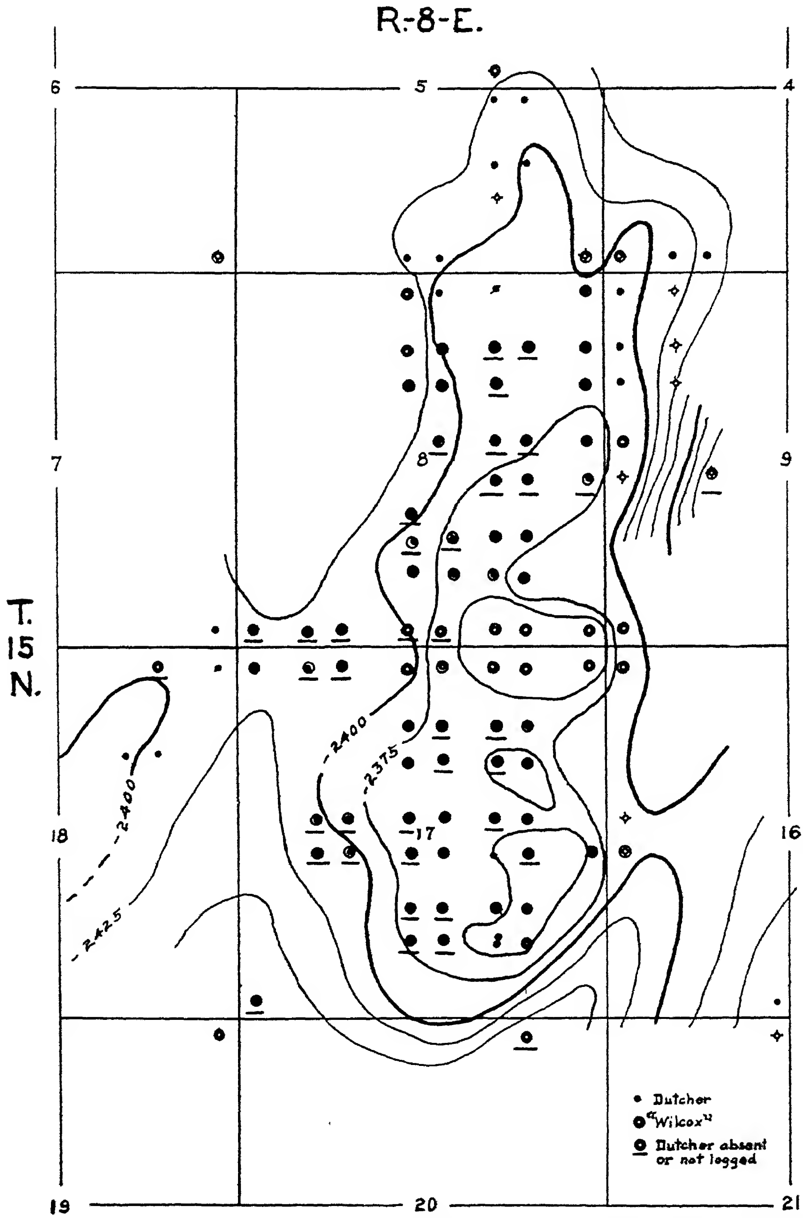

FIG. 5.—Subsurface contour map on top of Dutcher sand, below sea-level. Contour interval, 25 feet. Width of area mapped, 2 miles.

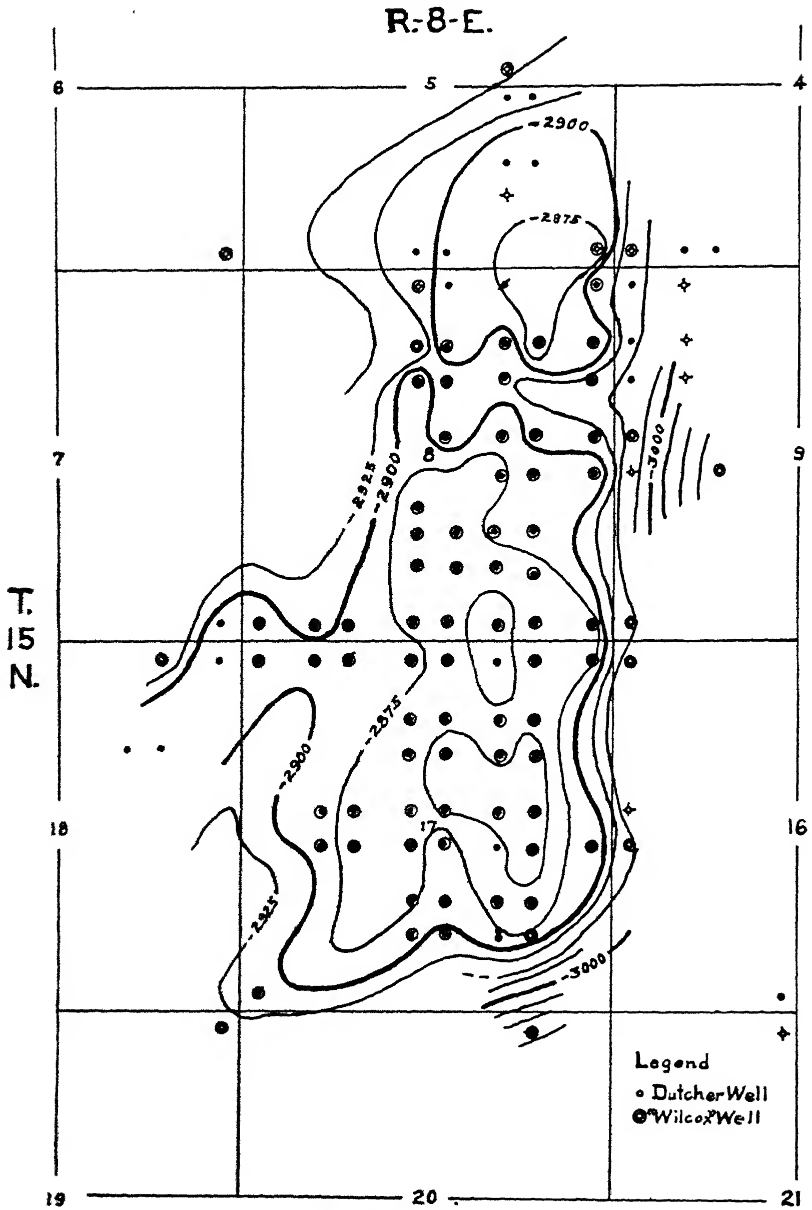

FIG. 6.—Subsurface contour map on top of "Wilcox" sand. Contour interval, 25 feet. Width of area mapped, 2 miles.

drilled 100 feet into the Bartlesville sand with a hole full of water and was abandoned early in 1913 at a depth of 2,884 feet. In 1915, a dry hole was drilled in Section 14 through the Fort Scott and was abandoned at 2,720

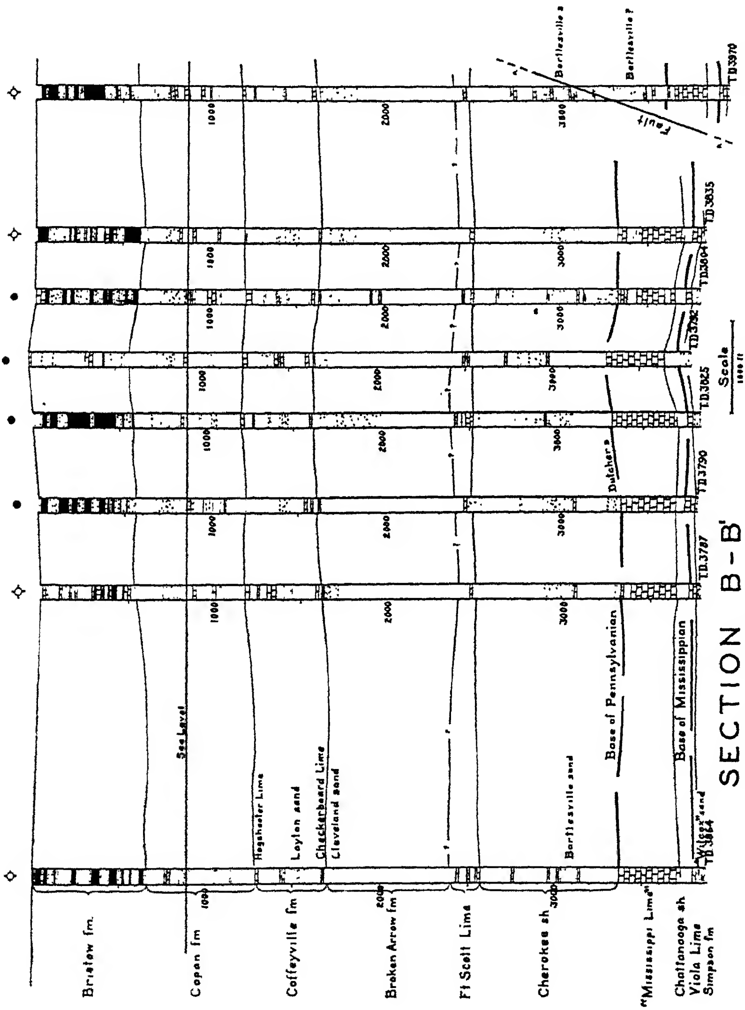

FIG. 7.—Cross section *B-B'* across Depew fold, showing possible position of fault. Depths in feet. For location, see Figure 3.

feet. The discovery well of the Poor Farm pool was the Wilcox Kelley No. 1, in the SE. ¼, SW. ¼, SE. ¼, Sec. 35, T. 16 N., R. 8 E., which was drilled to the Dutcher sand at 3,117 feet in January, 1921, and had an initial production of 250 barrels. Total recovery from the wells on the Kelley

lease (to mid-summer, 1928) was 269,266 barrels. The discovery well is now plugged and abandoned. In May, 1922, the Roland Oil Company completed its Alex No. 2 (NE. $\frac{1}{4}$, NW. $\frac{1}{4}$, SW. $\frac{1}{4}$, Sec. 2, T. 15 N., R. 8 E.) in the Dutcher sand at 3,148 feet, with an initial production estimated to be between 8,500 and 10,000 barrels. Total recovery from this well is estimated at 500,000 barrels. It is now abandoned. That gas pressure was the important factor in the Dutcher production in the vicinity of the phenomenal Roland well is shown by the fact that the east and north offsets of the well drilled two months later were good (2,400 barrels) wells, but the north and southwest offsets, drilled a year later, were dry holes, although the top of the sand was higher in both wells than in the Roland well and the north offset (Carter Lou Cat No. 2) was drilled 36 feet into the sand. The Carter Oil Company deepened Lou Cat No. 6, which had had an initial production in the Dutcher sand of 3,687 barrels, to the "Wilcox sand" and completed a 71-barrel well. The well reached the "Wilcox" at 3,665 feet and was drilled to 3,775 feet, but production was in the top of the formation. Other wells of the Poor Farm pool, which have been deepened to the "Wilcox," have been light producers. Total recovery from the Poor Farm pool is placed (summer of 1928) at 5,830,611 barrels, an average of 14,950 barrels an acre. The M. Harjo lease of the Wilcox Oil Company, in Sec. 35, T. 16 N., R. 8 E., with an average recovery of 19,092 barrels an acre, has been the best lease.

The Depew pool was opened late in 1922 by the Hiram Oil Company with its Robberson No. 1 in the northeast quarter of Section 8, which produced from 1,800 to 2,000 barrels from the Dutcher sand at 3,234 to 3,238 feet and in ninety days had produced 283,000 barrels, the largest Dutcher well in the pool. About eight months later, this well was deepened to the "Wilcox" and produced 30 barrels from 3,730 to 3,798 feet. The well at present produces 55 barrels a day from both sands. The "Wilcox" discovery well was the Gypsy Oil Company's Willie Wild Cat No. 1 in the NE. $\frac{1}{4}$, SE. $\frac{1}{4}$, Sec. 8, which reached the "Wilcox" sand at 3,801 feet and had an initial production of 300 barrels, natural. Both these wells are on the eastern edge of the pool. The most prolific "Wilcox" wells are in Section 17, the top of the "Wilcox" fold, which, as stated elsewhere in this report, is slightly west of the axis of the Dutcher "high." The largest producer, The Pure Oil Company's Yahola No. 2, penetrated the "Wilcox" sand from 3,742 to 3,798 feet, and, when shot, flowed 1,680 barrels. "Wilcox" production has ranged from 15 to 60 barrels a day on the edge of the pool to 200 to 1,000 barrels a day in Section 17. The total recovery from the

Depew pool was (summer of 1928) 7,616,090 barrels, an average of 8,462 barrels per acre, mainly "Wilcox" oil.

The producing sand of the gas field in Section 30 is the Dutcher. The gas field probably represents the extension of the fault zone east of the Depew field and possibly the area of "scissoring" along the fault. The wells in Section 26 produce from a sand (Prue? Wheeler?) in the Fort Scott zone. Production in the small pools in Sections 10 and 15 is mainly from the Dutcher, as in the Poor Farm pool. Scattered wells in Sections 20, 22, 27, 29, 30, and 35, which were drilled to the "Wilcox," are dry. Other scattered wells in Sections 22, 23, 25, 34, and 35 produced from the Layton, Cleveland, and Prue sands. Wells in Sections 20, 22, 27, 29, 30, and 35 drilled to the "Wilcox" are dry, the chief "Wilcox" production of the area being restricted to the Depew pool. The Prue structure, extending from T. 14 N., R. 8 E., into Secs. 34 and 35, T. 15 N., R. 8 E., is no evidence of underlying "Wilcox" structure, as the Prue is a lenticular sand. Only deeper drilling in the southeast quarter of the township will prove the presence of "Wilcox" oil.

AN OIL FIELD IN T. 25 N., R. 8 E., OSAGE COUNTY, OKLAHOMA[1]

C. D. STEPHENSON[2]
Tulsa, Oklahoma

ABSTRACT

The field here described, located in the southwest portion of T. 25 N., R. 8 E., Osage County, Oklahoma, produces oil from three formations, each bearing a different but definite relation to the geologic structure. All of the reservoir rocks are salt-water-bearing off of the local folds and oil-bearing on the higher parts of the closed structures. The field furnishes an excellent example of oil and gas accumulation governed by the principles of the anticlinal theory.

INTRODUCTION

The area described in the following report is situated in Secs. 19, 20, 21, 29, 30, and 31, T. 25 N., R. 8 E., Osage County, Oklahoma, about 15 miles southwest of Pawhuska. The field is interesting in that it produces oil and gas from three formations each having a different relation to the local structure. The field was originally explored as three separate folds, but at the present time the oil production in one horizon extends almost continuously throughout the area. Figure 1 shows the general location of the area.

All of the exploratory drilling and geological work with which the writer is familiar was guided by *U.S. Geological Survey Bulletin 686*, which shows the geological surface structure of T. 25 N., R. 8 E.

The writer is indebted to the oil and gas department of the Osage Indian Agency and to the companies operating in this field for some of the data used in this report.

STRATIGRAPHY

Outcropping formations.—The formations exposed in this field are Pennsylvanian in age. Approximately 200 feet of a vertical geological section was used in the structural mapping. Within this section occur five limestone beds, any one of which might be used as a thoroughly reliable

[1] Presented by title before the Association at the Tulsa meeting, March 26, 1928. Manuscript received by the editor, July 28, 1928. Published by permission of The Galt-Brown Oil Company.

[2] The Galt-Brown Oil Company.

key bed. The writer used the Bird Creek limestone, as it was the most widely distributed.

Subsurface formations.—Formations of Ordovician, Mississippian, and Pennsylvanian age have been encountered by drilling in the area. Subsurface maps have been made on four horizons, namely, the top of the Layton sandstone, the base of the Oswego limestone, the top of the Burgess sand, and the base of the Chattanooga shale. With the exception of the Chattanooga shale, the names just previously used are drillers' terms and appear in many well records. Figure 2 shows the formations encountered by drilling and the average depth at which they are found.

FIG. 1.—Index map of Oklahoma showing area covered by this paper.

The Layton sandstone has been correlated with the Coffeyville[1] formation which crops out in R. 14 E., Washington County, Oklahoma. The Layton sandstone as reported by well logs in this area has a maximum thickness of 50 feet. It contains irregular lenticular beds of shale. This formation everywhere in this field contains gas, oil, or water. Where wells are completed as commercial gas or oil wells, the Layton sand is generally not penetrated more than 20 feet. It is found at an average depth of 1,050 feet.

The Oswego limestone of the drillers' records has been correlated with the Pennsylvanian Fort Scott[2] limestone. In this field it has a thickness of 65 feet and is found at an average depth of 2,050 feet.

[1] G. C. Clark and C. L. Cooper, "Oil and Gas in Oklahoma," *Oklahoma Geol. Survey Bull. 40-H* (1927), p. 22.

[2] C. N. Gould, "Index to the Stratigraphy of Oklahoma," *Oklahoma Geol. Survey Bull. 35* (1925), p. 65.

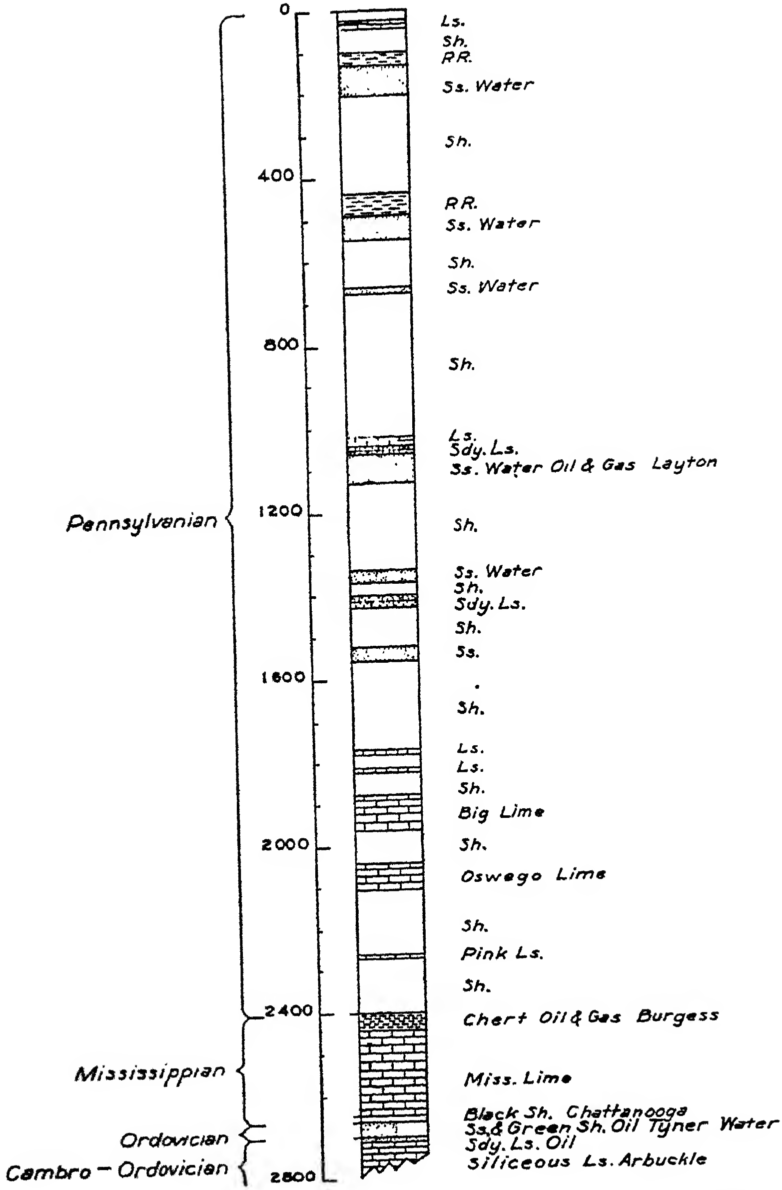

FIG. 2.—Composite record of wells in Secs. 19, 20, 21, 28, 29, 30, and 31, T. 25 N., R. 8 E., Osage County, Oklahoma. Depth in feet.

The Burgess sand, which is the main producing horizon of this field, is shown by samples to be chert and is probably the equivalent of the Boone chert (Mississippian). This chert, where non-productive of oil, or productive of gas, is ordinarily logged as limestone because of its white color and other lithological characteristics. Where the chert is productive of oil, it is commonly logged as sand because it does not effervesce in acid; and if oil is present, the cuttings resemble in shape and size a very coarse-grained sandstone. The Burgess sand is the uppermost member of the formation known in Osage County as the "Mississippi lime," and is found at an average depth of 2,400 feet. The Burgess sand is approximately 40 feet thick.

The Chattanooga shale, the base of which has been used as a reliable subsurface-marker, is not recognized in drillers' logs, but is reported as black limestone, together with the black Mississippian limestone lying immediately above. This error probably results from the facts that the Mississippian limestone and the Chattanooga shale have a very similar black color, that this shale is quite as difficult to drill as the limestone, and that the shale is slightly calcareous, effervescing in acid. The age of the Chattanooga is Mississippian.[1] The base of the Chattanooga shale is readily recognized by drillers from the marked change in the lithological features of the underlying formation and the ease with which the latter is penetrated by the drill. The Chattanooga shale is about 20 feet thick throughout this area.

The Tyner[2] formation (Middle and Upper Ordovician) is encountered below the Chattanooga. The Tyner is made up of alternating beds of green shale and sandstone and beds containing both shale and sand. In the locality of this report the formation has a uniform thickness of 25 feet. The sand grains are largely egg-shaped and have a frosted appearance, features which make them easily differentiated from other sandstones in the area. The "Hominy" (Burgen) sandstone is found in the Tyner formation. This sandstone is reported to produce oil wells of large initial production in this field and other parts of Osage County.

The oldest formation encountered in this field is locally known as the "Siliceous lime." This formation correlates with the "Turkey Mountain" and Arbuckle[3] limestone (Cambro-Ordovician). This limestone has not been penetrated by any well in this field, but the records of wells in the

[1] G. S. Buchanan, "Distribution and Correlation of the Mississippian," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 1308–10.

[2] C. N. Gould, *op. cit.*, p. 56.

[3] F. L. Aurin, *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 4 (1920), p. 177.

general area indicate a normal thickness in excess of 500 feet. In some areas this thickness is materially reduced at locations which are structurally high. The cuttings of this formation are peculiarly fine-grained and have the appearance of sand, for which the formation is commonly mistaken. The limestone is dolomitic. In fragments secured from wells which have been shot, the formation is megascopically observed to be very porous. The top of the "Siliceous lime" has been productive of very large oil wells in Osage County.

The formations described are present throughout the area of this report, with little or no differences in thickness on or off the structurally high areas. Regionally the Tyner formation thins toward the north and thickens toward the south. At the center of T. 26 N., R. 8 E., it is absent, and the Chattanooga shale is in contact with the "Siliceous lime."

Local sources of oil.—The Pennsylvanian shales in contact with the Layton sandstone offer a source for the oil found in this formation.

The Cherokee shale (Pennsylvanian), the probable source of Bartlesville-sand oil, overlies the Burgess sand and is the source of the oil found in the latter.

The oil in the Tyner formation and the oil in the "Siliceous lime" probably have a common source. The most probable source for this oil is the Chattanooga shale, as the Tyner formation here is predominantly sand with a little green shale, and the "Siliceous lime" is not sufficiently carbonaceous.

SURFACE STRUCTURE

In Osage County the normal surface dip is W. to N. 75° W. at an average rate of 45 feet to the mile. Eastern Osage County, of which R. 8 E. is the approximate western edge, is closely folded throughout, with features ranging from noses to anticlines with as much as 80 feet of closure. Several prominent folds and faults are found at the surface in R. 8 E., and this line of folding is underlain by prominent subsurface folds which may be traced south to the southern boundary (T. 21 N.) of Osage County. Five wells on this line of folding are reported[1] to have encountered granite at regionally shallow depths. The report has been verified by the writer for two of the wells, namely, the Marland Refining Company and Kay County Gas Company's No. 1 in SE. ¼, NE. ¼, Sec. 16, T. 24 N., R. 8 E., which encountered what was probably weathered granite at 2,480 feet and unweathered granite at 2,526 feet, and The Gled Oil Company's No. 3 in SE. ¼, NE. ¼, NE. ¼, Sec. 16, T. 24 N., R. 8 E., which

[1] F. C. Greene, *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 9 (1925), p. 351.

encountered granite at 2,710 feet. These two wells are about 4 miles south of the area here described.

West of T. 25 N., R. 8 E., there is a marked decrease in the amount of folding, there being probably less than one-sixth as many folds and even fewer faults in the general area extending 20 miles toward the west.

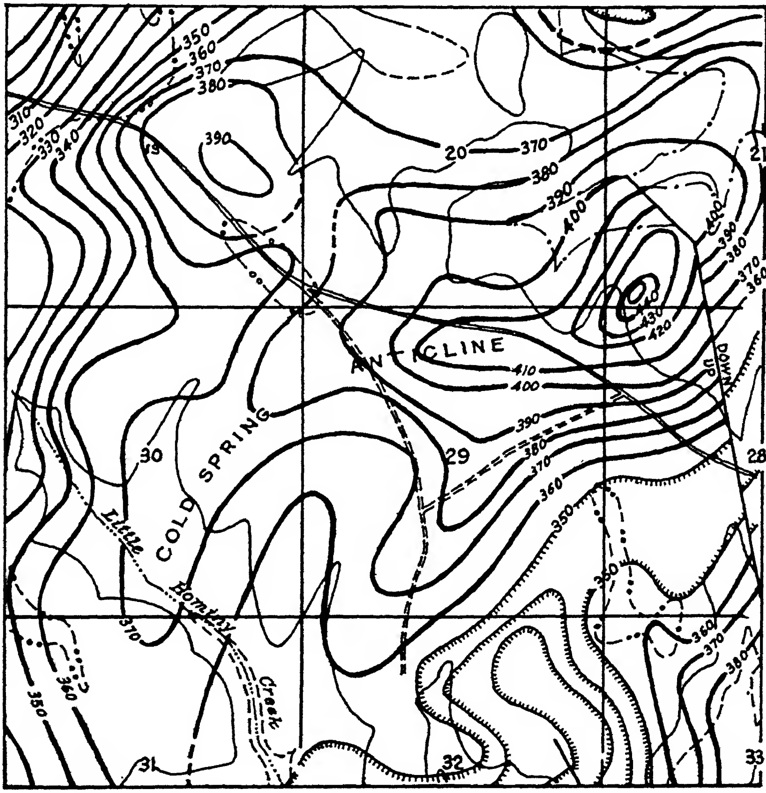

FIG. 3.—Map showing surface structure of part of T. 25 N., R. 8 E., Osage County, Oklahoma, after *U. S. Geol. Survey Bull. 686*. Checked in reconnaissance and detail. Width of area mapped, 2½ miles.

Figure 3 shows the surface structure of the field as mapped in *U.S. Geological Survey Bulletin 686*.

The writer has checked a portion of this area, using a plane table and alidade, and the results of this mapping are shown in Figure 4. Other geological maps which have been accessible closely approximate the work shown in Figure 4. The remainder of the area shown in Figure 3 and not

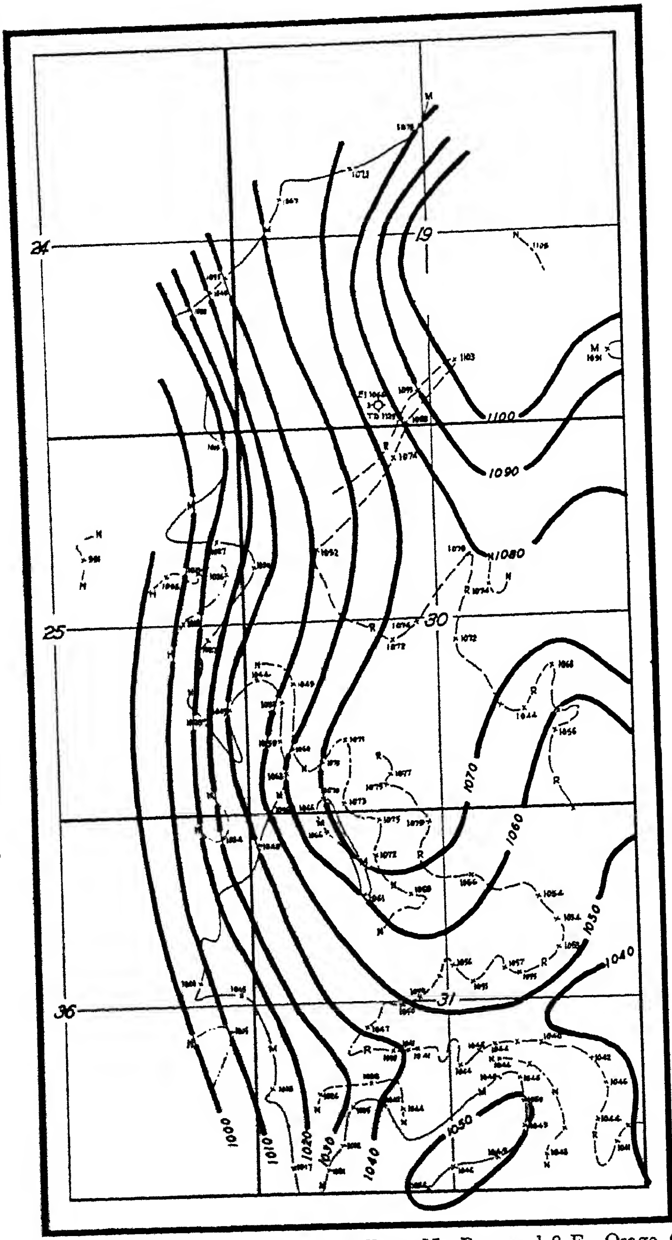

FIG. 4.—Surface structure of part of T. 25 N., R. 7 and 8 E., Osage County, Oklahoma, contoured on the Bird Creek limestone. Width of area mapped 1½ miles.

shown in Figure 4 has been checked in reconnaissance by the writer, and the work shows essentially the same structure. It will be observed that the prominent features of the surface structure are two closed domes and a long, pronounced nose.

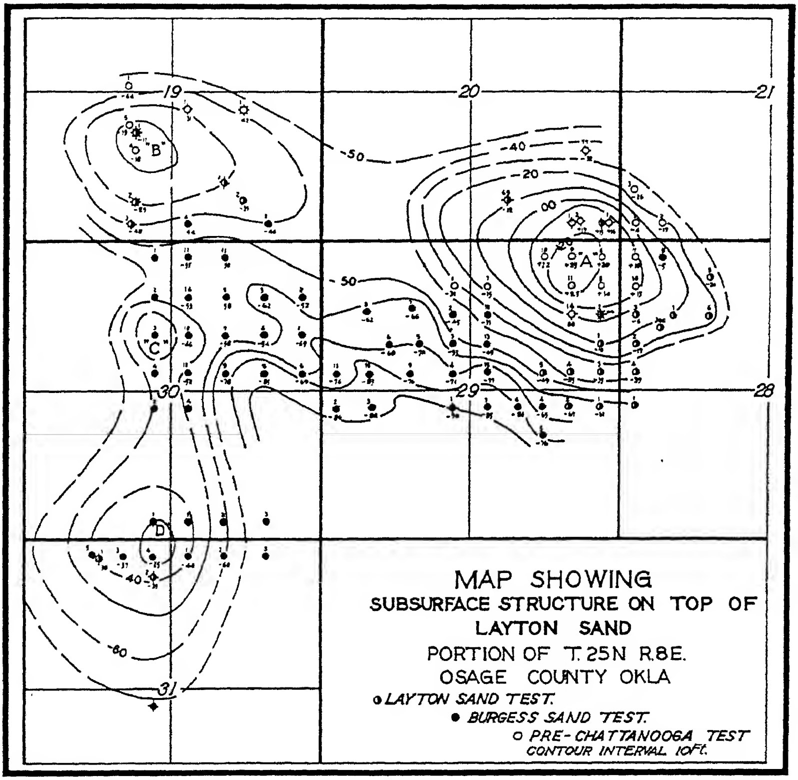

FIG. 5.—Map showing subsurface structure on top of Layton sand. Width of area mapped, 2½ miles.

SUBSURFACE STRUCTURE

Figures 5, 6, and 7 display the subsurface structure as mapped on the Layton sand, the Burgess sand, and the base of the Chattanooga shale, respectively.

In all of the subsurface maps, wells producing from different horizons are indicated by different symbols. The structure of these formations is very similar. The structures as revealed by the Burgess and by the Chattanooga are of almost equal steepness, and both are steeper than the

structure shown by the Layton. There is some thinning of the section between the Layton sand and the Burgess sand over the tops of the domes. The nonconformity which is known to occur in other localities at three different horizons, from the top of the Mississippian limestone into the top of the "Siliceous lime," is not present within the limits of this field.

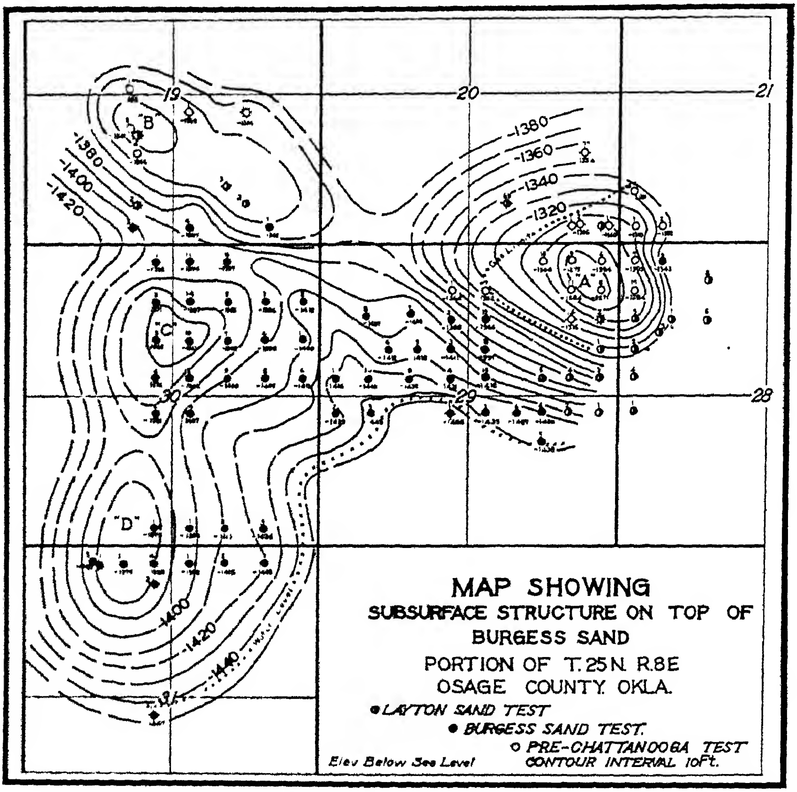

FIG. 6.—Map showing subsurface structure on top of Burgess sand.

Given an accurate depth (samples and steel-line measurement) for the top of the Burgess, the writer has found it possible closely to predict the depth at which any of the lower formations will be encountered, using the same thickness for lower beds in all wells. It is believed that irregularities in this field are due to inaccurate records rather than to actual differences in the thickness of formations. This uniformity of thickness for Mississippian and older formations has been observed in other fields in this area.

The tops of closed subsurface domes in this area are shifted toward the west or southwest of the tops of the surface domes (compare Figures 5, 6, and 7 with Figures 3 and 4). This shifting was found on five closed domes in T. 24 and 25 N., R. 8 E.

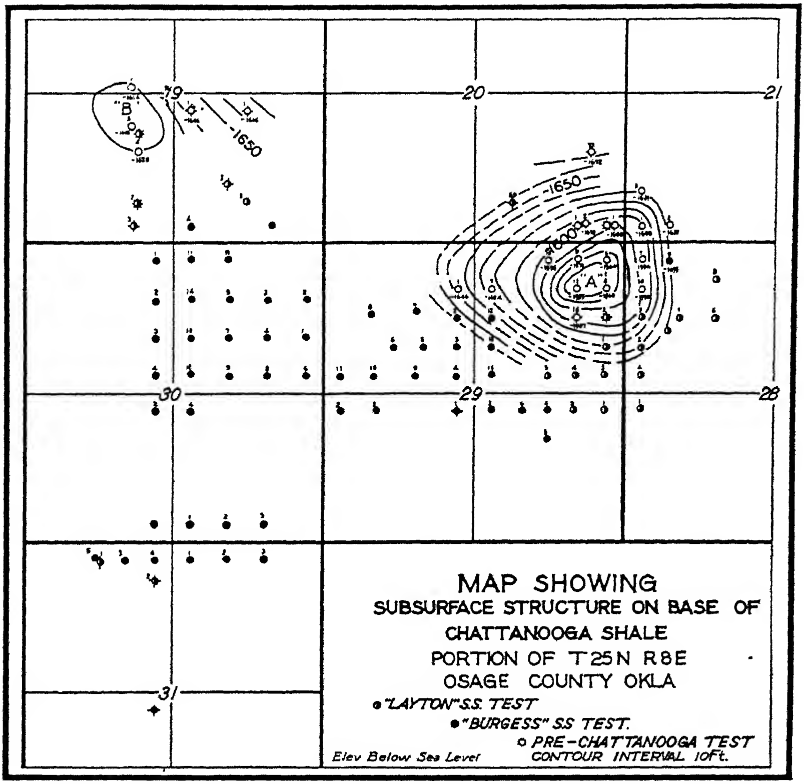

Fig. 7.—Map showing subsurface structure on base of Chattanooga shale.

FAULTING

There are several lines of *en échelon* normal faults in Osage County. The lines of faulting trend N. 25° E., although most of the individual faults have a trend N. 30° W. The line of faults in R. 8 E. mentioned in the paragraph describing the regional surface geology is one of the most prominent in Osage County. Faults in this line have a maximum vertical displacement of 90 feet.

A fault is present on the east side (Fig. 3) of the field. It has a vertical displacement of 30 feet, and the downthrow is on the northeast side.

Starting at the south end of the surface reflection, this fault plane trends N. 10° W. for approximately 6,200 feet, where the trend makes an abrupt turn N. 45° W. and continues for 1,700 feet. The writer has mapped very similar changes of fault-plane direction at other localities in Osage and Pawnee counties. This feature also appears on many of the plates showing surface structure in *U.S. Geological Survey Bulletin 686.* Because no wells have been drilled in a suitable location, it is impossible to tell whether the fault in this field is present in the underlying formations. Subsurface work elsewhere in T. 25 N., R. 8 E., shows that some faults which are present at the surface are also present in the Mississippian limestone. A study of the records of the two wells in this field drilled nearest to the surface fault shows that neither drilled through the fault plane. The faulting here is not older than late Pennsylvanian.

There seems to be no relation between faulting and oil or gas production in the field. Other fields in the immediate area where no faults exist have the same oil accumulation phenomena.

ORIGIN OF FOLDS

A widespread difference of opinion exists as to origin of domes and other structural features of the northeastern Mid-Continent oil and gas field, and many articles[1] have expressed reasons for different theories.

The writer believes that most of these folds are the result of rotational stress, probably transmitted through the basement complex. The forces acted several times during geologic history on the same lines of weakness. The fact that a majority of these folds have the same direction (northeast) for their major axes favors this theory. The lines of *en échelon* faults with parallel trends (N. 25° E.) and individual fault-plane trends (N. 30° W.) suggest a common origin in rotational stress. N. W. Bass[2] shows one area where faults which are probably due to slumping over buried hills or into solution cavities have no parallel trends. In most of the fields of Osage County with which the writer is familiar, it has been found that on the top of closed domes, or anticlines contoured on the top,

[1] L. L. Foley, "The Origin of the Faults in Creek and Osage Counties, Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 293–303; A. E. Fath, "The Origin of Faults, Anticlines, and Buried Granite Ridge of the Northern Part of the Mid-Continent Oil and Gas Field," *U. S. Geol. Survey Prof. Paper 128-C* (1920); H. D. Hedberg, "The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 1035–72; R. W. Brown, "Origin of the Folds of Osage County, Oklahoma," *ibid.*, Vol. 12 (1928), pp. 501–13.

[2] "Geologic Investigations in Western Kansas," *State Geol. Survey of Kansas, Bull. 11* (1926), pp. 44–49.

the Mississippian is shifted toward the west or southwest of the top of the surface structure closure. This shifting suggests folding by rotational stress rather than settling over buried hills or compression with equal pressure acting from all directions. In some areas, settling over buried hills undoubtedly contributed to the forming of the anticlines and domes of the northern Mid-Continent fields, but the writer believes that these hills were caused by stresses and that they have been enlarged by repeated action at different times.

RELATION OF PRODUCTION TO STRUCTURE

The oil and gas found in the three producing horizons of this field all have a definite relation to the structure, but each horizon differs markedly from the others in this relation. All of the reservoir beds are widespread deposits and carry salt water in this field where encountered low in the structure.

For convenience, references to the four domes shown on the subsurface maps in Figures 5, 6, and 7, are lettered as follows: in the northeast quarter of Section 29, *A;* in the southwest quarter of Section 19, *B;* in the northwest quarter of Section 30, *C;* and in the northwest quarter of Section 31, *D.*

The Layton sand produces gas on the tops of all four domes. Oil production in this sand has been confined to the south and southeast flanks of domes *A* and *B*. Wells drilled low on these domes carry salt water in this horizon. This field is the only area within the four adjacent townships which produces oil of importance in the Layton sand. Many other structural conditions favorable for accumulation of oil and gas have been unsuccessfully tested in this formation. It is suggested that the squeezing of the shales in the pronounced syncline in Sections 32 and 33 (Fig. 3), south of this Layton sand production, is the local condition which furnished the oil. The location of the production on the domes indicates a migration from this direction.

The Burgess sand has produced oil, gas, or salt water within certain definite structural limits in this area. Domes *A* and *B* produce only gas on the tops; the oil production occurs well down the flanks. Domes *C* and *D* are structurally lower with reference to domes *A* and *B*, and the Burgess sand produces oil on the tops of the former domes. Figure 6 shows the lower level of the gas and the water level. Any well which encounters the Burgess sand at less depth than 1,360 feet below sea-level produces predominantly gas. Well No. 10, in northeast quarter of Section 30, closely approaches this level and produces a large amount of gas but very little

oil. Wells encountering this formation at greater depth than 1,440 feet below sea-level produce salt water. At present there has been no noticeable encroachment of the water level. The oil production in this horizon was here originally found on the southwest flank of dome *A* and has gradually extended along the south flanks of domes *A* and *B* and the east flanks of *C* and *D*. Within the past year oil production has been extended to the tops and slightly down the west flanks of domes *C* and *D*. It is predicted that oil production will extend down the west and southwest flanks of domes *B*, *C*, and *D* until it reaches a plane where the Burgess is found at greater depth than 1,440 feet below sea-level. The largest Burgess sand wells have been found between the 1,380-foot and 1,410-foot contours (Fig. 6). The oil seems to have migrated to these domes from the south and west.

The oil production secured below the Chattanooga shale occurs only on the very tops of domes *A* and *B*. There is some doubt whether the pre-Chattanooga oil is from the Tyner formation or the "Siliceous lime." Samples from most of the deep wells on domes *A* and *B* indicate that the oil horizon is the "Siliceous lime." Samples from the No. 1 well in the southwest quarter of Section 21 show only sand and green shale of the Tyner formation, but the writer believes that these may not represent the actual producing zone. This well began flowing at the rate of 2,000 barrels a day after drilling through a hard shell. The securing of reliable samples is difficult in large flowing wells. The oil-producing horizon is less than 5 feet thick. The salt water in this zone is structurally much higher than that in the Burgess sand.

Salt water is encountered in one of the Tyner sands on dome *A*, 5 feet above the oil-producing horizon. Generally, in this field, the higher structurally a well is located the more water is encountered in the Tyner, and the larger the oil well when the producing horizon is reached. Wells on dome *B* had no water in the Tyner, and the "Siliceous lime" oil wells averaged about one-fifth as large as the average well from the same formation on dome *A* where water was encountered in the Tyner. This feature was also observed on another subsurface dome in Sec. 6, T. 24 N., R. 8 E., 3 miles south of the field here reported. In Sec. 6, T. 24 N., R. 8 E., wells on top of the closure had a hole full of water in the Tyner formation above the oil horizon, and wells drilled on the flanks of the dome had decreasing amounts of water. Wells drilled 50 feet structurally lower than the top closure had no water in the Tyner formation and did not produce oil in the "Siliceous lime." This phenomenon is not explained by the writer but is here mentioned as an observed fact.

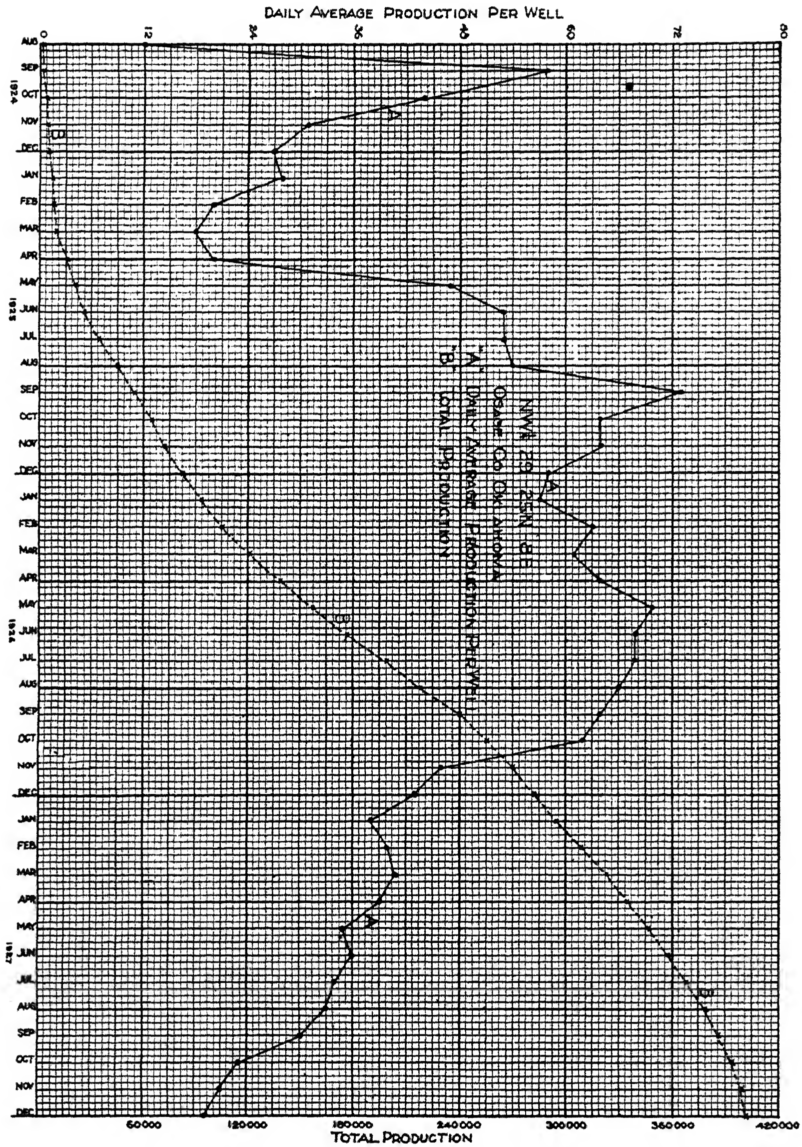

FIG. 8.—Production curves NW. ¼, Sec. 29, T. 25 N., R. 8 E., Osage County, Oklahoma.

Domes *C* and *D* have not been tested below the Burgess sand, but both will probably produce oil in pre-Chattanooga formations. Because these domes are much lower than domes *A* and *B*, it is believed that the deep wells will not produce as profitably as those on dome *A*.

OIL AND GAS PRODUCTION

The Layton sand gas wells in this field have an average initial production of 2,000,000 cubic feet daily, and the oil wells have a daily production varying from 50 to 100 barrels daily after an average nitroglycerin shot of 60 quarts. The gravity of the oil is 39° Bé. It is customary to pump Layton sand wells.

The oil produced from the Burgess sand varies in gravity from 39° to 41° Bé. Casinghead gasoline is also profitably produced from this formation, but no figures are available as to the exact amounts. Small shots ranging from 10 to 15 quarts of nitroglycerin have been used in about one-third of these wells. Ninety per cent of the two-year-old Burgess wells are still flowing.

Figure 8 shows a total production curve and a curve indicating a daily average production per well for the northwest quarter of Section 29. This lease produces only from the Burgess. Eleven wells on this quarter-section had an average initial production of 140 barrels daily. By June 1, 1928, a yield of 4,000 barrels per acre had been obtained in four years.

Production data for the northeast quarter of Section 30 are shown by Figure 9. This tract also produces only from the Burgess sand. In the first eighteen months, ending January 1, 1928, fourteen wells on this lease had produced 4,000 barrels to the acre. These wells had an average daily initial production of 228 barrels.

The production secured in other tracts producing from the Burgess sand had the following average daily initial production:

	No. of Wells	Av. I.P. Barrels
NW. ¼, Sec. 30	4	159
SW. ¼, Sec. 30	2	236
SE. ¼, Sec. 30	4	175
NW. ¼, Sec. 31	3	303
NE. ¼, Sec. 31	3	154

Production in these tracts is comparable with that found in the northeast quarter of Section 30, which is shown in Figure 9. While most of the leases producing from the Burgess are in the process of development and predictions of the yield per acre are uncertain, the past production here

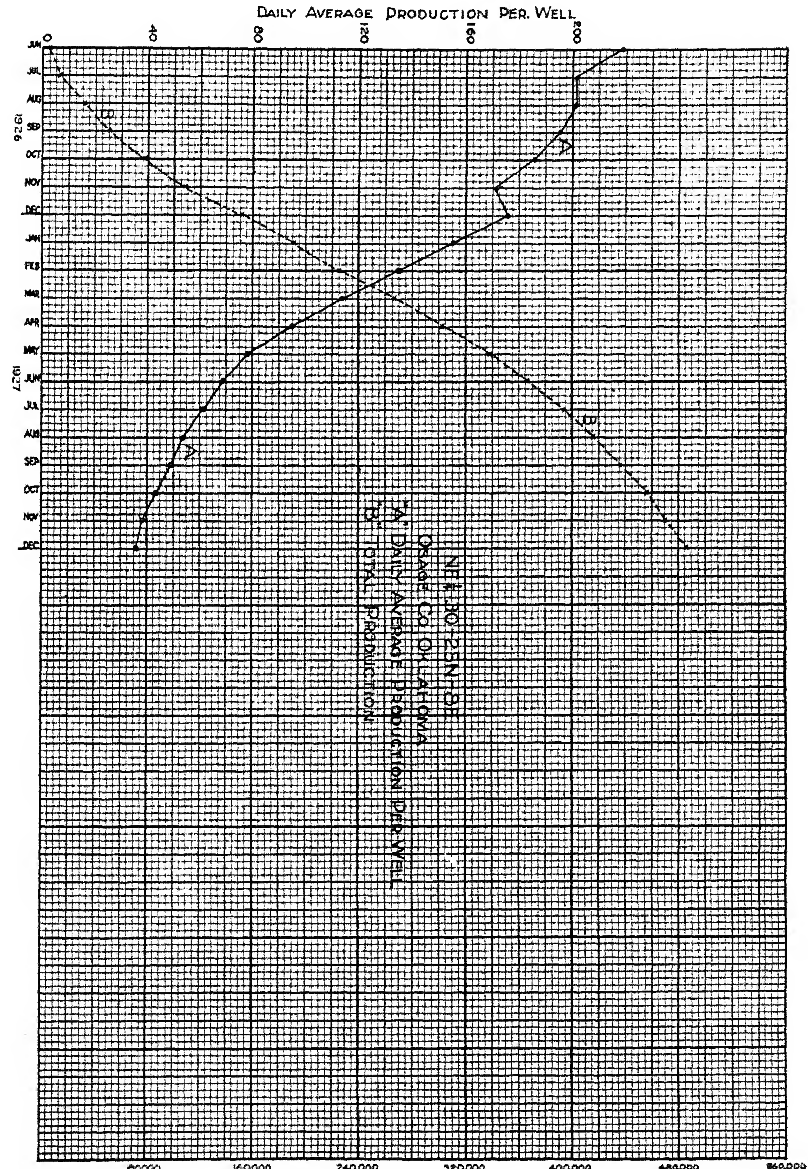

FIG. 9.—Production curves NE. ¼, Sec. 30, T. 25 N., R. 8 E., Osage County, Oklahoma.

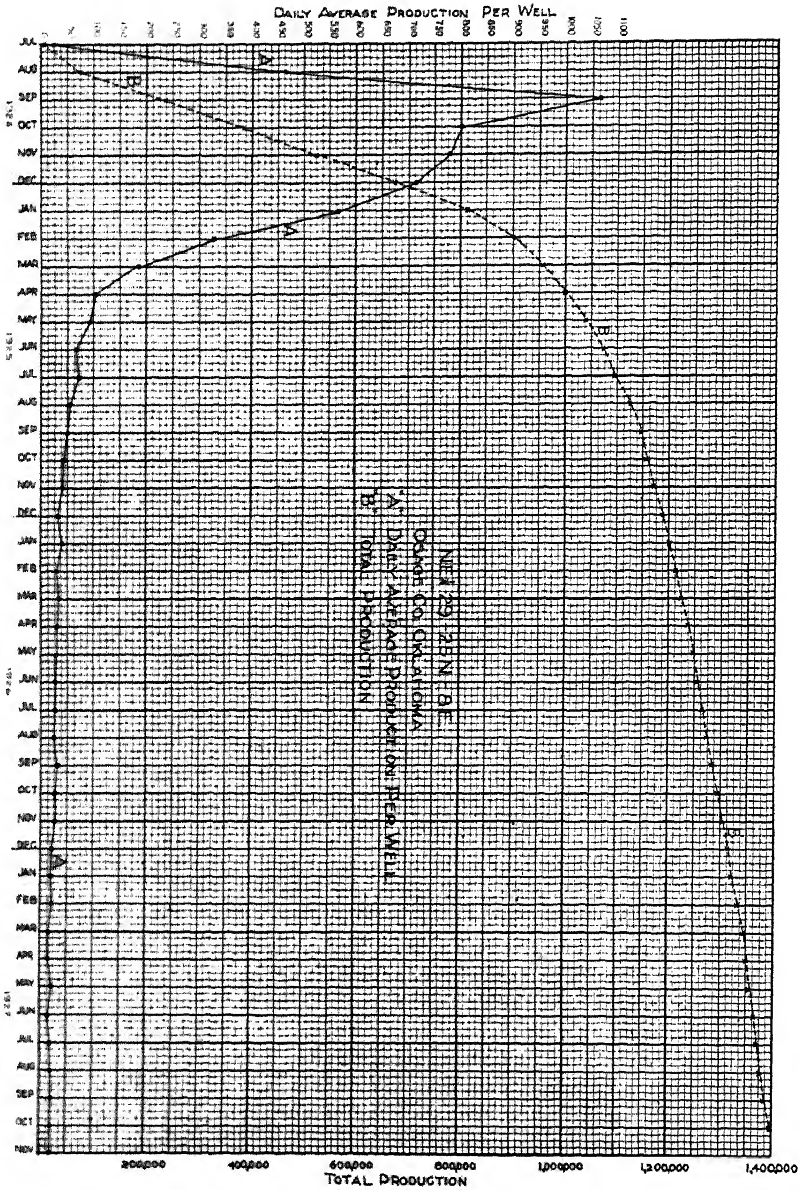

FIG. 10—Production curves NE. ¼, Sec. 29, T. 25 N., R. 8 E., Osage County, Oklahoma.

and in other Burgess fields warrants an estimation of 10,000 barrels to the acre for the Burgess sand in this field.

Figure 10 shows production curves for the northeast quarter of Section 29. It will be noticed that in ten months after the completion of the first pre-Chattanooga well on this lease three more wells producing from the same horizon were completed and a total production of 1,000,000 barrels had been secured. Although some production has been obtained from the Burgess and Layton sands on this lease, approximately 95 per cent of the oil here produced is from the "Siliceous lime." These wells had initial productions ranging from 600 to 6,000 barrels daily. The small area producing from the "Siliceous lime" on this lease has yielded more than 20,000 barrels to the acre in four years. The oil tests 41° Bé. The wells have a rapid decline and produce large amounts of salt water with the oil after they are one year old. It is ordinarily necessary to pump the "Siliceous-lime" well after a short period. Most of the operators in this area produce "Siliceous-lime" oil through small orifices, and a back pressure is carried on the well.

CONCLUSIONS

The accumulation of oil and gas in this field is the direct result of anticlinal folding, although the relation of production to the structure differs in the different producing horizons. The migration of the oil seems to be the result of oil seeking the structurally high locations by a separation from salt water due to the differences in specific gravity. The tops of the subsurface domes are slightly west of the tops of the surface domes, but the search for productive areas may be guided by surface structure.

CUSHING OIL AND GAS FIELD, CREEK COUNTY, OKLAHOMA[1]

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Tulsa, Oklahoma

ABSTRACT

The Cushing oil and gas field has produced nearly 300,000,000 barrels of oil since the completion of the discovery well in 1912. This amount is exceeded only by two other continuous fields in the United States. Accumulation of oil in the field is due to the presence of an anticline 20 miles in length. The producing area comprises 34 square miles. The average yield per acre to January 1, 1928, was 12,993 barrels. Previous publications relative to the Cushing field have not discussed in detail the unconformable relation between the Pennsylvanian strata and underlying rocks. At the Dropright dome, the Bartlesville sand (lower Pennsylvanian) rests on the Arbuckle limestone (lower Ordovician). This unconformable condition is present but less pronounced throughout the entire field. The pre-Pennsylvanian rocks on the east limb dip at a rate of 15°. The west flank dips at a rate of less than 2°. Several erosion cycles have affected the rocks in the Cushing district. The fold was probably present as an anticline at the end of Arbuckle time. Local history of movement cannot be traced during Ordovician, Silurian, Devonian, or Mississippian time. In early Pennsylvanian time the Cushing anticline was again uplifted. Subsequent erosion of the newly formed anticline resulted in the typical concentric distribution of outcrops about the anticlinal axis. The base-leveled anticline was later covered by the advancing early Pennsylvanian sea. Gentle uplifting occurred contemporaneously with the deposition of the Pennsylvanian rocks. The predominant west dip of surface beds throughout the region suggests a westward tilting of the Cushing anticline at some time after the deposition of the Pawhuska formation, outcroppings of which occur in the Cushing field.

INTRODUCTION

GENERAL STATEMENT

The Cushing oil and gas field occupies an area of 34 square miles in T. 16, 17, 18, and 19 N., R. 7 E., in the northwestern part of Creek County, Oklahoma.

The discovery well was drilled by C. B. Shaffer on the Wheeler farm, Sec. 31, T. 18 N., R. 7 E., and was completed in March, 1912. The location was later found to be on an anticline. The discovery of oil and gas on this and other anticlines was an early stimulus to petroleum geology in the northern Mid-Continent region and led to the introduction of the term "on structure" for reference to wells located on anticlines.

[1] Published by permission of the Tidal Oil Company. Manuscript received by the editor, February 28, 1928.

[2] Divisional chief geologist, the Tidal Oil Company.

Previous literature is available embodying the early history and development of the field.[1] The present paper is devoted to more recent findings and conclusions.

ACKNOWLEDGMENTS

The writer is greatly indebted to the many Oklahoma geologists whose data and materials have been invaluable in the preparation of this paper. James N. McGirl and his staff of the Silurian Oil Company have been especially helpful, having furnished much material and many drill cuttings from about twenty-five wells in the vicinity of the Dropright dome, where subsurface geology cannot be interpreted by the ordinary well-log correlation methods.

OIL AND GAS PRODUCTION

Oil and gas occurs at the crest of the anticline in the Layton, Jones, Wheeler,[2] Prue, Skinner, Red Fork,[3] and Bartlesville sands of Pennsylvanian age and in the "Wilcox" (Tucker) sand[4] and Arbuckle limestone[5] of Ordovician age.

The Layton sand produces throughout an area of 14 square miles. Due to the prolific productivity of deeper sands, the Layton horizon was given little attention at the crest of the anticline. The Wheeler lime produces mainly on the west flank of the anticline. Production from this horizon was short-lived, and many wells were abandoned after producing but a year. The areal extent of production from the Wheeler covers nearly 11 square miles. In the Cushing field proper the production of oil from the Prue, Skinner, Red Fork, and Jones sands was insignificant in amount. Production in the Skinner sand is limited to Secs. 2 and 3, T. 18 N., R. 7 E., and the southeast part of T. 19 N., R. 7 E. The Bartlesville sand produces throughout an area of approximately 28 square miles. Production

[1] Frank Buttram "The Cushing Oil and Gas Field, Oklahoma," *Oklahoma Geol. Survey Bull. 18* (1914); Carl H. Beal, "Geologic Structure in the Cushing Oil and Gas Field," *U. S. Geol. Survey Bull. 658* (1917); D. P. Wardwell *et al.*, "Water Problems in the Northern Part of the Cushing Field, Creek County, Oklahoma," U.S. Bur. of Mines, mimeographed report (February, 1927).

[2] The Wheeler "sand" is a limestone and is generally correlated with the upper member of the Oswego limestone.

[3] The Red Fork sand is commonly designated as the "Squirrel sand" in the Cushing field. The latter is equivalent to the Prue sand and obviously is not to be correlated with the Red Fork sand.

[4] The term "Wilcox" sand is used in the text of this paper to include all of those closely associated sands of Ordovician age, the Burgen, Tyner, and "Wilcox."

[5] Known also as "Siliceous lime."

of oil and gas from the "Wilcox" sand and Arbuckle limestone is restricted to the very crests of the domes. It is significant that the Arbuckle limestone produces only on the Dropright dome, where the "Wilcox" has been removed.

Total production of the entire field to January 1, 1928, was 283,894,274 barrels from 21,850 producing acres, an average yield of 12,993 barrels per acre. The total recovery is exceeded by only two other fields in the United States, the Midway-Sunset and Coalinga fields of California. The peak of daily production of 305,000 barrels was reached in May, 1915, the field then being three years old. Daily production on January 1, 1928, was 21,050 barrels from 2,375 wells. These figures are but approximate, owing to unrecorded wastes of oil during early stages of development and the possible addition of production from near-by fields.

Development of the Cushing field occurred during an extraordinary period of Bartlesville-sand exploitation in Oklahoma. The Nowata, Bartlesville, Glenn, and eastern Osage County fields gave the Bartlesville sand a distinction for productivity unexcelled by any other oil sand. Cushing added fame to this horizon.

Recovery of oil from each individual sand at Cushing cannot be differentiated. Total average yield from the Bartlesville sand would certainly not exceed 8,000 barrels per acre. Later in the present discussion the Bartlesville sand will be shown to be resting unconformably upon the "Wilcox" sand and other Ordovician beds. Oil from the "Wilcox" sand may have migrated through this unconformable contact into the immediately overlying Bartlesville sand, lending a greater quantity of oil to the latter than was normally present.

STRATIGRAPHY

SURFACE

The Pawhuska and Buck Creek formations of late Pennsylvanian age crop out within the area. Limestone members of the Pawhuska formation are generally used as key horizons for surface mapping.

SUBSURFACE

The underlying Pennsylvanian section is composed mainly of shales, with alternating limestone and sandstone beds.

Unfortunately, very poor records of formations penetrated were kept during early stages of operations in the field. No drill cuttings were saved. More recent exploitation for deeper horizons has been the means of supplying samples of the pre-Pennsylvanian section. The so-called

"Tucker" sand lies at intervals from immediate contact with the base of the Bartlesville sand to 200 feet below it. Samples of the "Tucker" sand exhibit all the characteristics of the "Wilcox" sand. The individual grains are rounded and frosted. In some samples the sand grains are intermingled with green shale. The "Tucker" sand rests on a dolomitic limestone of Arbuckle age, which in turn rests on pre-Cambrian granite. Stratigraphically, then, as well as lithologically, the "Tucker" sand is a drillers' misnomer for "Wilcox" sand. At the Dropright dome, centering in the northwest part of T. 18 N., R. 7 E., the "Tucker" sand is in reality Arbuckle limestone in juxtaposition to Bartlesville sand (Fig. 4). This unconformable condition of lower Pennsylvanian rocks resting on Ordovician strata is present in a similar manner in other Oklahoma and Kansas fields, as Cleveland, Tonkawa, Garber, Thomas, Hubbard, Blackwell, Augusta, and El Dorado. Absence of the Mississippian section and identity of the Ordovician rocks at Cushing was originally reported by Aurin, Clark, and Trager.[1]

STRUCTURAL GEOLOGY

The surface is characterized by an anticline with a north-south axis, in general (Fig. 1). On the anticline are four distinct domes. The main axis includes the Dropright, Drumright, and Shamrock domes. The Mount Pleasant dome acts as a "spur" from the main anticline.

The underlying Pennsylvanian rocks are folded similarly except that divergence of beds basinward causes greater steepening of dip with depth. These slightly incompetent rocks rest unconformably on the underlying beds (Fig. 2).

It is difficult to choose a pre-Pennsylvanian datum for contouring, as each has been truncated from the axis of the fold. The writer has chosen the upper surface of the "Wilcox" sand as the most feasible key horizon in the absence of critical samples, inferring its attitude over the crest of the domes where the horizon is no longer present (Fig. 3).

The pre-Pennsylvanian fold is characterized by a steep east flank, the beds being inclined 15° from the horizontal (Figs. 4, 5, 6). The west flank, on the other hand, is dipping westward gently except in the vicinity of the Dropright dome.

The east limb of the anticline dips so steeply as to suggest faulting. However, logs of all wells within the area of steep dip exhibit gradually

[1] F. L. Aurin, G. C. Clark, and E. A. Trager, "Notes on the Subsurface Pre-Pennsylvanian Stratigraphy of the Northern Mid-Continent Oil Fields," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 5 (1921), pp. 131–33.

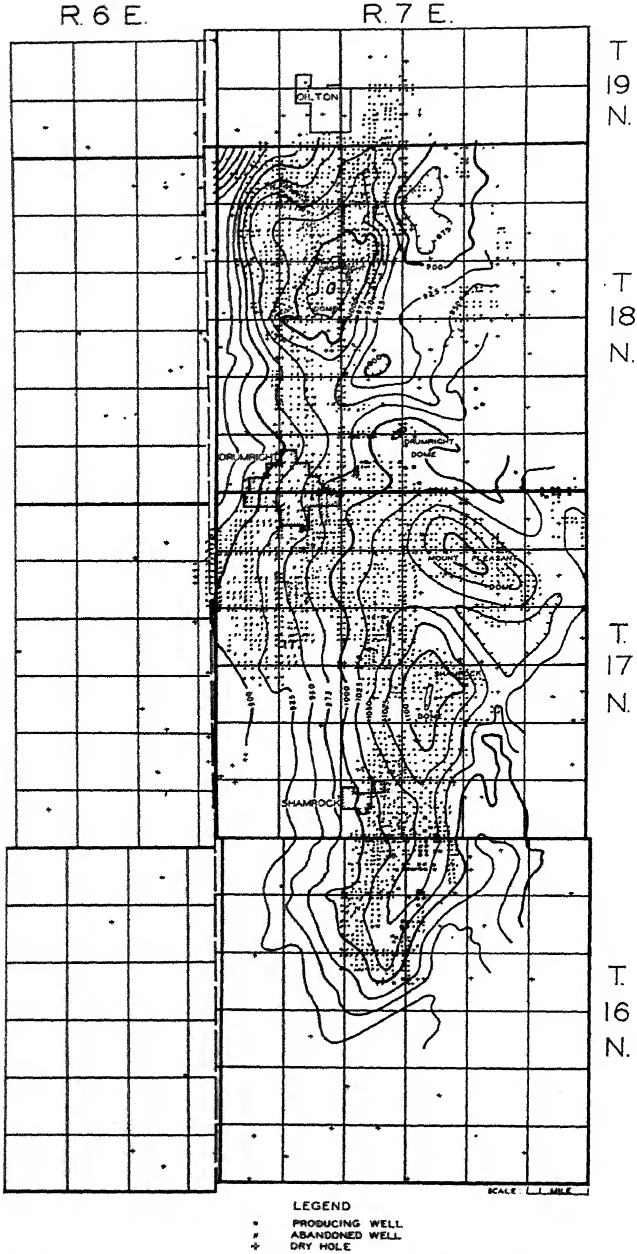

FIG. 1.—Structure contour map of surface rocks in the Cushing field. Copied from map by Carl H. Beal, *U. S. Geol. Survey Bull. 658* (1917). Contours based on upper surface of Pawhuska limestone; contour interval, 25 feet.

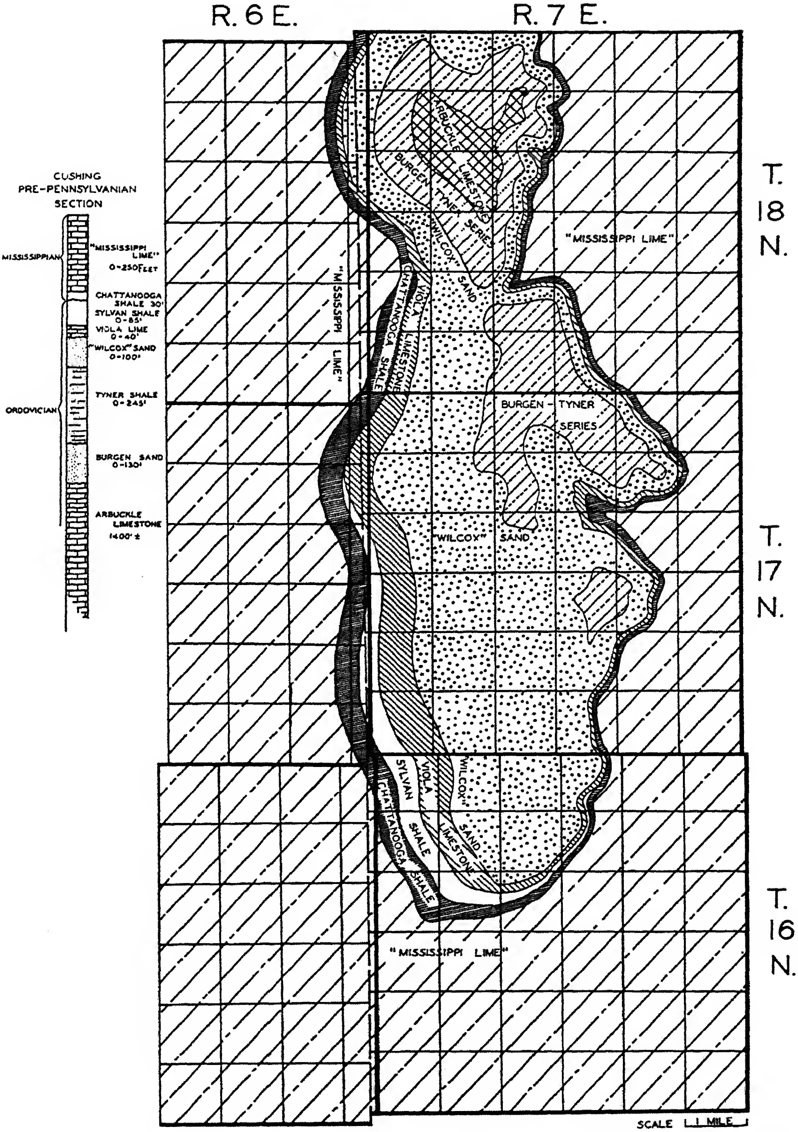

FIG. 2.—Areal distribution of pre-Pennsylvanian rocks in the Cushing field. The Chattanooga shale (Mississippian) overlaps the Sylvan shale (Ordovician) along the south line of T. 18 N., R. 6 E., and in the northeast part of T. 16 N., R. 7 E. The Viola limestone is similarly overlapped in the northeast part of T. 18 N., R. 7 E. The map also illustrates approximately the areal geology of the district in early Cherokee time.

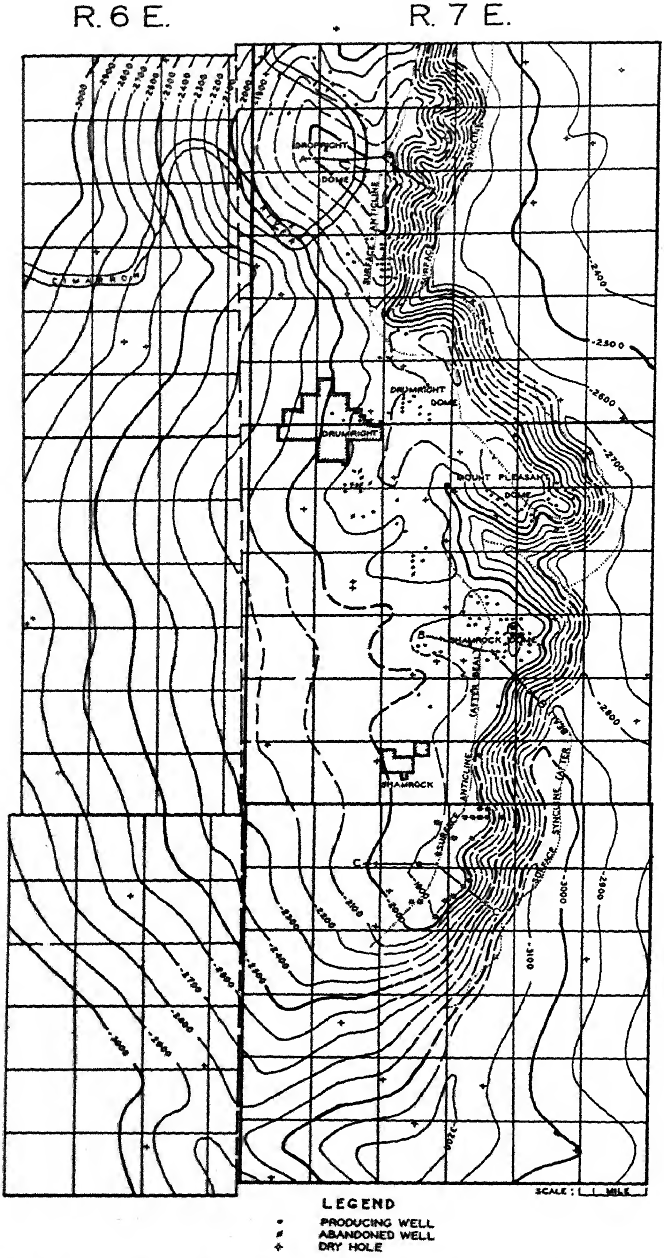

FIG. 3.—Structure contour map of pre-Pennsylvanian rocks in the Cushing field Contours based on upper surface of "Wilcox" sand; contour interval, 100 feet. Contours are inferred at the crests of the domes where the "Wilcox" sand has been removed

shortened pre-Pennsylvanian sections as compared with those farther from the anticlinal crest. One would suppose that, if faulting is present, the section would maintain its normal thickness to the fault plane on the downthrown side. Furthermore, the area of steep dip does not follow a straight line as would be expected in the case of faulting. The cross sections illustrated in Figures 4, 5, and 6 are constructed with the vertical and horizontal scale alike. Exaggeration of the vertical scale increases the rate of dip so perceptibly that faulting seems more reasonable than steep dip.

HISTORICAL GEOLOGY

Several wells in the general region have encountered pre-Cambrian granite. Presence of arkosic débris is noticed immediately overlying the solid granite. Resting unconformably on the arkosic material is the Arbuckle limestone of Cambro-Ordovician age. A regional period of erosion is known to have existed at the close of Arbuckle time. At Cushing 1,405 feet of Arbuckle limestone is present in a well drilled on the Dropright dome. On the Shamrock dome, a structurally lower point, only 630 feet is present. The latter thickness indicates the presence of a truncated fold in the vicinity of the Shamrock dome structurally higher than the surrounding region at the close of Arbuckle time, or a pre-Cambrian hill over which the normal thickness of Arbuckle limestone was never deposited.

Transgression of the sea during the remainder of Ordovician time resulted in the deposition of Simpson, Viola, and Sylvan formations, with intermittent periods of erosion. The thickness (about 600 feet) of these beds in central Oklahoma is slight as compared with that of the same section in the Arbuckle mountains on the south. In the latter region the post-Arbuckle Ordovician rocks have a maximum thickness of about 3,000 feet. This difference in thickness may be accounted for partly by truncation at intervals progressively lower into the section, partly by convergence of strata, proceeding northward. At Cushing the Simpson section is represented by the Burgen, Tyner, and "Wilcox" formations, with a maximum thickness of approximately 475 feet. In the Arbuckle mountain region the Simpson section has a maximum thickness of about 2,000 feet. From this evidence it seems probable that the floor of the Arbuckle region was being depressed, or northern Oklahoma was being elevated relatively, during the entire period of Ordovician time.

Events during Siluro-Devonian time are unimportant for the present purpose. Evidence indicates that an unconformity exists between Silurian and Devonian rocks. At the close of Devonian time the rocks of

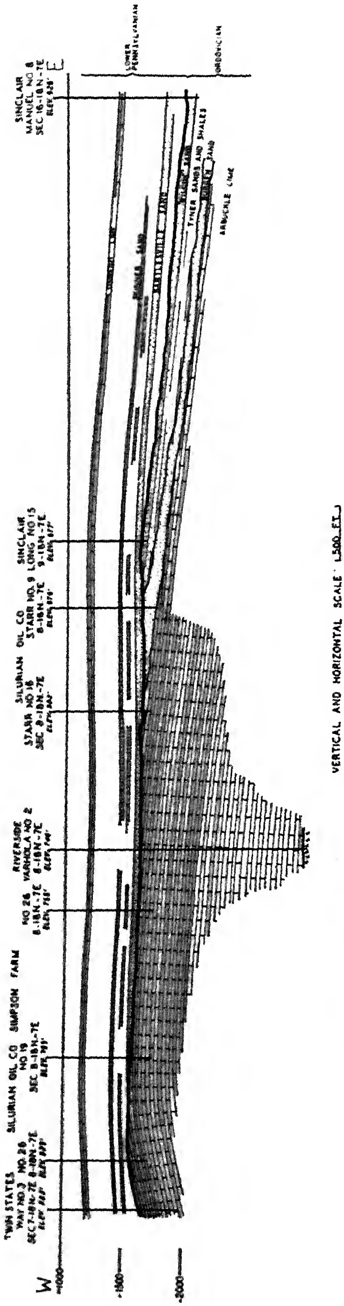

FIG. 4.—West-east cross section, *A–A* (Fig. 3), through the Dropright dome. The Bartlesville sand rests unconformably on upper Arbuckle limestone and other Ordovician beds. Elevations and depths shown in feet.

northeastern Oklahoma were further uplifted,[1] inclining the strata into a southwestern dip in the vicinity of Cushing. Exposure of these strata resulted in their truncation progressively lower in the section northeastward. The close of this erosional period found the exposed strata forming typical belts of monoclinal structure. The northern limit of Siluro-Devonian rocks extended across northern Okfuskee and northeastern Lincoln counties. The underlying Sylvan shale cropped out in a broad belt traversing the southwestern part of T. 17 N., R. 7 E. The Viola limestone, the succeeding lower formation, was exposed throughout the present area of the Cushing field but was completely eroded in the northeastern part of T. 18 N., R. 7 E. It is possible that the Shamrock dome was rejuvenated at this time into an anticline, but the evidence is obscure because later folding and subsequent erosion were much more pronounced and produced steeper dips.

Submergence of these beveled strata resulted in deposition of the Mississippian Chattanooga shale and the "Mississippi

[1] Luther H. White, "Subsurface Distribution and Correlation of the Pre-Chattanooga ("Wilcox" Sand) Series of Northeastern Oklahoma," *Oklahoma Geol. Survey Bull. 40-B* (1926).

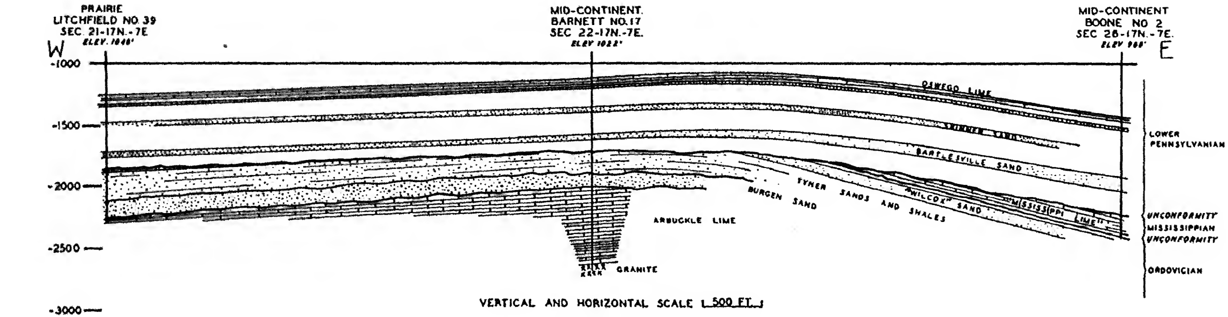

FIG. 5.—West-east cross section, *B–B* (Fig. 3), through the Shamrock dome. Drill cuttings from several wells on this dome clearly established the "Tucker" sand as being "Wilcox" or its associated sands. Elevations and depths shown in feet.

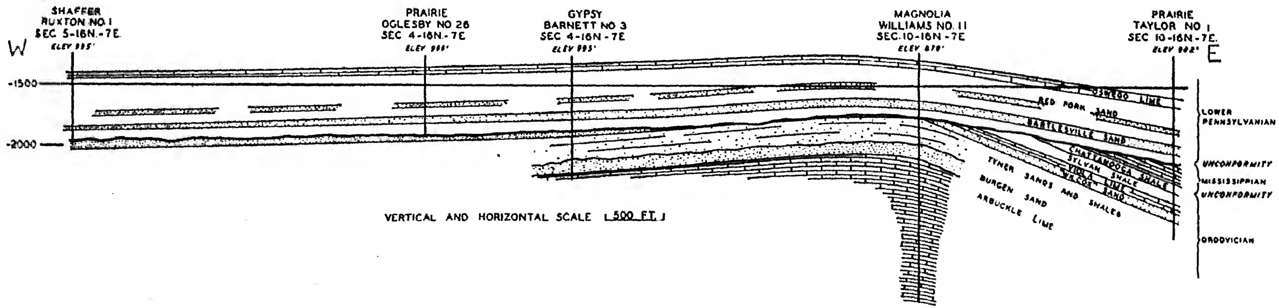

FIG. 6.—West-east cross section, *C–C* (Fig. 3), through the north part of T. 16 N., R. 7 E.

lime" and possibly a portion of the lowermost Pennsylvanian. The rocks at the end of this period of deposition suffered a most intensive warping, and the structure of the Cushing anticline for the first time assumed a detailed form similar to that now existing. The resulting areal geology, exposing all rocks from the pre-Bartlesville shales to the Arbuckle limestone, is illustrated in Figure 2.

Submergence and subsequent deposition of Pennsylvanian sediments over this abnormal arrangement of pre-Pennsylvanian strata continued throughout the remainder of the Paleozoic era. Divergence of beds basinward, together with an arching of the unconformable contact itself, indicates a gentle but continuous uplifting of the Cushing anticline throughout the Pennsylvanian epoch.

The last major movement to affect the Cushing district tilted the strata of the entire region westward, steepening the dip of beds on the west flank and moderating the reverse dip on the east flank of the Cushing anticline. For the present purpose it is sufficient to place the time of this uplift after the deposition of the Pawhuska formation.

Thus the local history of the building of the Cushing anticline indicates the existence of an anticline at the end of Arbuckle time overlying a pre-Cambrian granite hill; slight uplifting or cessation of sedimentation occurred spasmodically from the beginning of Ordovician to early Pennsylvanian time; renewed arching movements, initiated early in the Pennsylvanian, continued throughout the remainder of the Pennsylvanian period.

BRADFORD OIL FIELD, McKEAN COUNTY, PENNSYLVANIA, AND CATTARAUGUS COUNTY, NEW YORK[1]

JERRY B. NEWBY,[2] PAUL D. TORREY,[3] CHARLES R. FETTKE,[4] AND L. S. PANYITY[5]
Oklahoma City, Oklahoma, and Bradford and Pittsburgh, Pennsylvania

ABSTRACT

The Bradford oil field is of peculiar interest for several reasons. It is located about equidistant between the place where oil was first discovered in America and the famous Drake well. Its 85,000 acres of continuously productive territory from the Bradford sand, its 25,000 producing wells, and its fifty-five years of productive history make it one of the most outstanding oil fields of the world. It has received much publicity because of the successful use of water-flooding for increasing oil recovery within the past twenty years. The field was opened in 1871, and the peak of production was reached in 1881, when 23,000,000 barrels of oil were produced. The present production is about 3,700,000 barrels per year.

The stratigraphic column of the Bradford oil field is limited to the Paleozoic. The principal oil-producing horizons are in the lower part of the Chemung formation of Upper Devonian age. The reservoir rocks are very fine-grained and tightly cemented sandstones. The most important sand, the Bradford, has an average thickness of 40 feet and an average porosity of approximately 15 per cent.

Two anticlines, plunging southward, and converging northward into the Knapp Creek dome, with a closure of approximately 250 feet, have been the dominating factor influencing oil accumulation in the Bradford sand. This structure was also a primary influence in the accumulation of oil and gas in the minor productive sands, although the irregular depositional character of these minor sands has been an important contributing factor in limiting production.

Bradford oil has an average gravity of 45.5° A.P.I. and is widely known for its high-grade lubricating fractions. Gas wells were rare in the original development of the field. On the Knapp Creek dome and at intervals along the crest of the anticlines, the upper part of the Bradford sand was a gas "pay." The original rock pressure was presumably subnormal, but data on this are indefinite. The Bradford sand thins out on the east edges of the pool. Elsewhere edge water is present. Encroachment has been so very slight that from existing operating records it is impossible to establish any definite rate.

INTRODUCTION

The Bradford oil field is in McKean County, Pennsylvania, and Cattaraugus County, New York (Fig. 1). The productive area of the field

[1] Read before the Association at the Tulsa meeting, March 25, 1927. Manuscript received by the editor, January 30, 1928.

[2] Consulting geologist, 721 Braniff Building, Oklahoma City, Oklahoma.

[3] Geologist, Northwestern Pennsylvania Oil Producers Association, Bradford.

[4] Geologist, Pennsylvania Geological Survey, Pittsburgh.

[5] Consulting geologist, Bradford.

covers more than 85,000 acres in which approximately 30,000 wells have been drilled. The chief producing sand is the Third, or Bradford. The

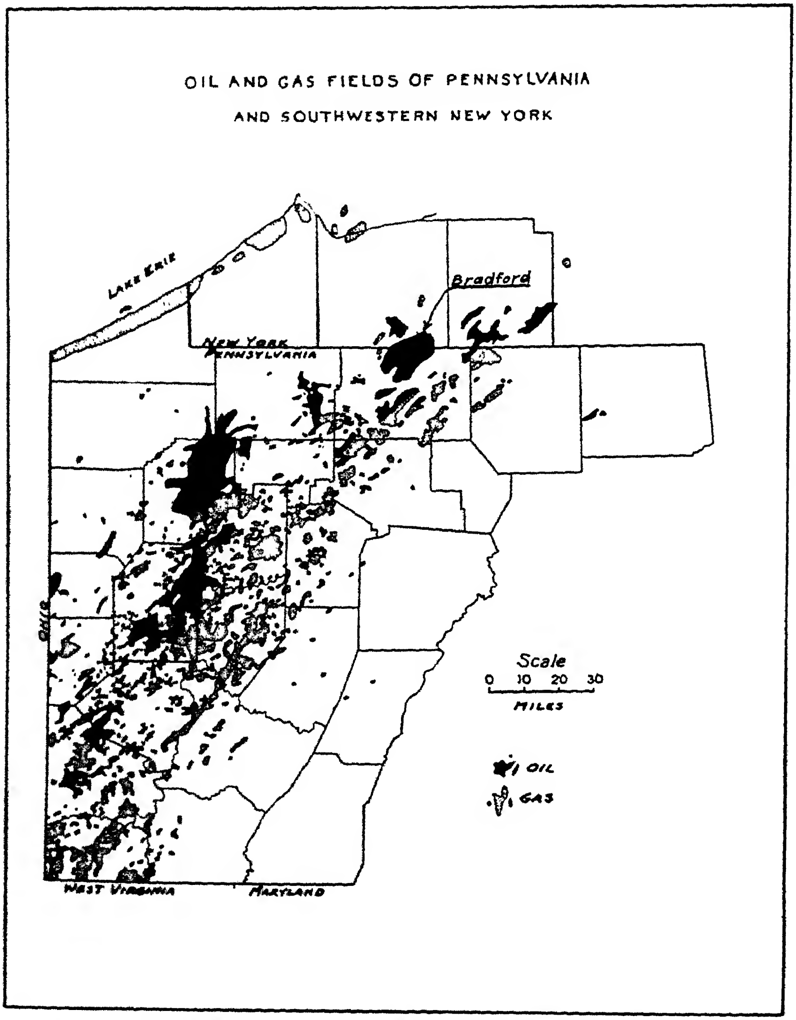

FIG. 1.—Oil and gas fields of Pennsylvania and southwestern New York, showing location of Bradford field.

writers wish to acknowledge the assistance of Charles Butts, of the U. S. National Museum, whose identification of fossils and stratigraphic studies have enabled a better classification of the rocks of this region. The Forest

Oil Company and several other operators at Bradford contributed data that were of great help. The information collected by Paul Torrey was assembled for the Northwestern Pennsylvania Oil Producers Association. That collected by Charles R. Fettke was assembled for the Pennsylvania State Geological Survey. Most of their data were kindly made available for this paper.

HISTORY

The history of petroleum production in the Bradford oil field and surrounding areas goes back to the early years of American history. On July 18, 1627, the Franciscan missionary Reverend de la Roche d'Allion wrote of the occurrence of oil at the Seneca Oil Spring near Cuba, New York. During the eighteenth and in the early part of the nineteenth century the oil from this spring, under the name "Seneca Oil," was widely marketed throughout the eastern states for medicinal purposes. A test well for oil was drilled near the spring to a depth of 600 feet in the spring of 1857. This well did not discover any commercial production, but it is believed to be the first well that was drilled specifically for oil on the North American continent, as it antedates the Drake well at Titusville by two years.

Following the discovery of oil in Venango County, there were sporadic attempts to develop production throughout the northwestern counties of Pennsylvania. During 1861 the first well was drilled for oil within the present Bradford pool. The following inscription was nailed to the derrick: "Oil, Hell, or China." It is reported that the hole was abandoned at 800 feet without discovering oil or reaching China.

Prospecting was continued, however, and in 1871 oil was discovered at a depth of 1,110 feet on the Foster farm 2 miles northeast of the city of Bradford. The well had an initial production of 10 barrels and is still making approximately $\frac{1}{8}$ barrel a day. This stimulated further drilling, and during the next four years sixteen wells were completed, which during 1875 had a total production of 36,000 barrels. Since that time development was extremely rapid, and during 1881 the peak of production was reached, which amounted to 23,000,000 barrels per year.

The period of flush production was followed by a gradual decline, which continued until 1907, when the first effects of flooding were noticed. For fifty-five years Bradford has maintained a continuous natural production of oil. Water-flooding at the present rate will extend the length of economically productive life at least another thirty years.

It is believed that flooding of the oil sand for increasing recovery was being secretly practiced as far back as thirty-five years ago, although at

that time most of the operators regarded the use of water with great alarm; and even at the present time there are some who oppose its use. On May 17, 1921, the present law legalizing water-flooding was approved by the governor of Pennsylvania.

PHYSIOGRAPHY

The area of the Bradford oil field is in the northern part of the Appalachian Plateau region adjoining the southern limit of Pleistocene glaciation. The plateau breaks off sharply south of the valley of Allegheny River; and although dissected by numerous streams, it maintains a fairly uniform elevation throughout the field. Erosion has advanced to a post-mature stage; and had it not been for the fact that the plateau level in most of the field corresponds in a general way with the outcrop of the Olean conglomerate and Knapp sandstone, most of the existing peneplain remnants would have been destroyed. The maximum elevation in the field is a little more than 2,400 feet above sea-level, which is approximately 1,000 feet above the elevation of the lower levels of the streams.

The field is drained by various tributaries of Allegheny River which flow in rather wide, flat valleys, bordered by small flood plains. There is no direct evidence of Pleistocene glaciation within the area covered by this paper, although a certain amount of the filling in the northern part of the stream valleys may be due to sediments deposited in temporary ponds formed along the front of the ice. Allegheny River valley lies east, north, and west of the field, a feature which is attributed in part to structural conditions and in part to glacial influence.

SURFACE STRATIGRAPHY

The rocks exposed in the Bradford oil field are of Pennsylvanian, Devono-Carboniferous, and Devonian age. They consist chiefly of shale and sandstone and a few inconspicuous beds of limestone. They include at the top some of the beds of the Pottsville group of Pennsylvanian age and at the bottom the upper part of the Chemung formation of Devonian age, an aggregate thickness of more than 1,000 feet.

PENNSYLVANIAN

The Pennsylvanian series of the Carboniferous system is represented by the Olean conglomerate and a few isolated outliers of the Sharon shale, both members of the Pottsville group.

Olean conglomerate.—The Olean conglomerate is by far the most distinctive and easily recognized formation in the entire section. Its type local-

ity is at Olean Rock City in the northern part of the field, where it crops out as a massive, coarse, white, quartz-pebble conglomerate. The lithologic character of the Olean is not uniform, either vertically or horizontally. In the northern part of the field it is uniformly conglomeratic, but toward the south pebbles become less common, and at Bingham in the southern part of the field, where it is excellently exposed in a cut of the B., R. & P. Railroad, it is a very cross-bedded, coarse, brown sandstone.

A very marked unconformity occurs at the base of the Olean. The lower contact, where exposed, is irregular, and at several places in the field the Olean can be observed definitely overlapping the underlying beds.

DEVONO-CARBONIFEROUS

The Knapp formation, Oswayo shale, and Cattaraugus formation are included in a Devono-Carboniferous series as classified by Butts.[1] The Knapp and Oswayo were originally placed in the Pocono of the Mississippian by Ashburner,[2] but this has been shown to be erroneous both by stratigraphic and paleontological evidence. The Cattaraugus was considered by Ashburner to be the equivalent of the Catskill, but this correlation is not definitely established. A very adequate discussion of the age of these formations is given by Butts in the Warren folio.[3] In addition to this it may well be stated here that none of the Mississippian beds of Pennsylvania has been recognized in this area. In the anthracite region of eastern Pennsylvania, the Pottsville has a thickness of approximately 1,350 feet, below which there is more than 4,000 feet of Mississippian sediments (Mauch Chunk and Pocono). This section thins within a short distance toward the northwest so that it is quite possible that none of the eastern Pennsylvania section of Mississippian sediments was laid down in this region. If beds of this series were at one time present, they were all removed during the long pre-Olean period of erosion. The Olean conglomerate has been generally regarded as equivalent to the upper part of the Pottsville.

Knapp formation.—The Knapp formation was first described by Glenn and Butts[4] from the type locality at Knapp Creek in the southwestern part of the Olean quadrangle. Here it occurs as two coarse-grained sandstones separated by a shale which is not uniform in thickness.

[1] Charles Butts, *U. S. Geol. Survey Folio 172* (1910).

[2] Charles Ashburner, "McKean County Report," *Second Pennsylvania Geol. Survey.*

[3] Charles Butts, *op. cit.*

[4] *Report of the New York State Paleontologist* (1902).

Toward the south it becomes a much more prominent member of the section and has been described throughout a large area as the sub-Olean conglomerate. The formation as a whole is rather easily recognized, but few individual beds can be traced for any distance because of marked variations in conditions of sedimentation and because of removal of many of the beds by pre-Pottsville erosion. In the extreme northeastern part of the Bradford field the entire formation was removed during this period of erosion. Such erosion also occurred at several localities farther west in Warren County.

The Knapp formation near the type locality is sparingly fossiliferous. The following collection was made by Charles Butts, paleontologist of the U. S. National Museum and the junior writer, approximately ½ mile southeast of Harrisburg in the Salamanca quadrangle.

Orbiculoidea	*Athyris polita*
Ortholetes	*Rhynchospira scansa*
Spirifer disjunctus	*Leptodesma orodes*
Syringothyris, sp.	*Leptodesma curvatum*
Camarotoechia, 2 or 3 sp. probably undescribed	*Alorisma*, sp.?
	Schizodus, sp.?

These fossils occur in characteristic Knapp sandstone, and this faunule is made the basis for limiting the formation in the southern part of the field.

South from Knapp Creek as far as the vicinity of the city of Bradford the formation is similar to that at the type locality except that only the lower sandstone member is present (the sub-Olean conglomerate of the Second Pennsylvania Geological Survey). The thickness in the hills around Bradford is approximately 75 feet. From Bradford to Bingham, in the extreme southern part of the field, the formation shows a very marked change in character. The massive coarse-grained sandstones and conglomerates practically disappear and are replaced by a series of alternating soft, olive-green shales and sandstones and near the base thin highly fossiliferous sandy limestones. The total thickness along the B. R. & P. Railroad north of Bingham is 190 feet. The upper part of the formation at this locality has yielded the following fossils.

Chonetes, cf. *C. burlingtonesis*
Schizodus, sp.?
Rhipidomella, cf. *R. oweni*

The *Chonetes* and *Rhipidomella* indicate a lower Burlington or a New Providence age. Several fossil collections from the lower part of the formation at the same general locality have yielded the following species.

Oehlertella pleurites
Orthotetes, sp.
Productus, sp.
Paraphorphynchus, sp.
Camarotoechia, 1 or 2 species
Spirifer disjunctus
Athyris polita
Rhynchospira scansa
Leptodesma curvatum
Leptodesma orodes
Leptodesma maclurii
Leptodesma, undescribed sp.
Dipterus minuta

Rynchospira scansa and *Athyris polita* in connection with plentiful *Camarotoechia* and *Leptodesma* tie this horizon with the Knapp sandstones near the type locality. The presence of *Productus* and *Paraphorhynchus* is notable. These two genera, together with *Syringothyris*, are rated as Mississippian fossils and appear in the Kinderhook beds, the basal Mississippian of the Mississippi Valley. They indicate the early Mississippian age of the Knapp formation.

Oswayo formation.—Beneath the Knapp beds is a series of soft, olive-green, thin-bedded, almost uniformly sandy shales with a few thin fine-grained, greenish-brown sandstones which constitute the Oswayo formation. The type locality is on Oswayo Creek in the southwest corner of Allegany County, New York. Fossils are fairly plentiful throughout the formation, the most characteristic invertebrate being *Camarotoechia allegania*, which is a most distinct horizon-marker. The base of the formation is placed at a very fossiliferous sandy limestone which crops out in a cut of the B. R. & P. Railroad south of Droneys Station. What is probably the same limestone was repeatedly found by Glenn and Butts[1] in the Olean and Salamanca quadrangles, New York, and it is probably the Marvin Creek limestone of Ashburner.[2] The thickness of the Oswayo ranges from 150 to 250 feet.

Cattaraugus formation.—The Cattaraugus formation consists of red and olive-green shales and sandstones. It is the Catskill of the Second Pennsylvania Geological Survey and is at least the lower part of the Conewango formation of the Warren quadrangle. The lower contact of the Cattaraugus is a most definite horizon, based both upon paleontological and stratigraphic evidence. The Wolf Creek conglomerate, the basal member of the Cattaraugus, contains a new and distinct fauna, for the most part entirely foreign to the Chemung. Furthermore, conditions of sedimentation were changed. The almost monotonously regular succession of marine shales, sandstones, and sandy limestones of the Chemung is followed abruptly by a series of continental deposits with a few marine members. Fossiliferous beds are fairly common within the area of the

[1] *Ibid.* [2] *Ibid.*

Bradford oil field, which is quite different from the section in Tioga County, Pennsylvania, where the formation is practically unfossiliferous. West of the Bradford field, the percentage of marine beds seems to increase. This change from strictly continental beds to marine is a complicating feature in the stratigraphy of the area and has caused much of the contention as to age of the formations above the Chemung. Devonian species do occur in the Cattaraugus, but, as has been pointed out by Butts,[1] the most characteristic fossils of the Chemung are not found in the Wolf Creek. It is, of course, quite probable that the Cattaraugus is equivalent to some part of the Catskill in the Catskill mountains, but the exact correlation is unknown. It also must be emphasized that individual members of the red-bed series are worthless as horizon-markers, changes in color being so numerous that they can be observed in many outcrops, even those of limited extent.

The Venango group of oil sands occurs in the Cattaraugus. What is believed to be the Third or Gordon sand crops out in the quarry of the Hanley Company at Lewis Run, Pennsylvania. At this locality it is a massive, hard, brownish-red, somewhat calcareous sandstone, conglomeratic at the top and base and containing numerous marine fossils. It has recently been discovered, from a study of diamond-drill cores, that the Second sand of the Venango group is also marine.[2] These sands have previously been regarded as non-marine, and the synclinal theory of oil accumulation in some of the Venango sands was based upon this assumption. The fact that the second and in all probability the third sand of the Venango group are marine sandstones is entirely in conformity with our present knowledge of the changing character of the Cattaraugus.

DEVONIAN SYSTEM

Chemung formation.—Since the outcrop of the Chemung is limited to the upper part of the formation, it will be described under "Subsurface Stratigraphy."

SUBSURFACE STRATIGRAPHY

Notwithstanding the fact that approximately 30,000 wells have been drilled in the Bradford oil field, little attention has been paid to logging any formations drilled except those which have contained oil and gas. Very good records are obtainable on several recent wells which were drilled below the Bradford sand for gas, and an excellent log was kept of

[1] Charles Butts, *U. S. Geol. Survey Folio 172.*

[2] Charles R. Fettke, *Amer. Inst. Min. Met. Eng., Petroleum Development and Technology in 1926*, p. 221.

the deep well at Derrick City, Pennsylvania, which was drilled to a depth of 5,820 feet, showing a practically complete Devonian and Silurian section. The majority of the wells go only to the Bradford sand, which is a basal member of the Chemung formation.

Chemung formation.—The oldest exposed beds and most of the horizons which are oil-bearing in the field belong to the Chemung formation. The rocks of the Chemung are chiefly soft, greenish-brown, micaceous and sandy shale alternating with many hard, thin, argillaceous sandstones. In the lower part there are several thicker and more persistent sandstones, which are the reservoir rocks of the Bradford and adjacent oil fields. The fact that these sands cover such considerable areas is in direct contrast to the lack of continuity of many of the horizons above the Chemung.

Up to within a very recent time definite knowledge as to the position of the Bradford sand in the stratigraphic section was lacking. Recent paleontological and stratigraphic studies have yielded considerable information as to the age of this horizon. Charles Butts has made the following report on fossils in samples of Bradford sand.

From Proctor No. 4 of the Pressure Oil Company:
Spirifer mesacostalis
Camarotoechia, sp.?
Edmondia obliqua?
From Hawkins No. 1-A-12 of the Petroleum Reclamation Company:
Productella lachrymosa?
Productella hirsuta?
Except for the *Spirifer*, the forms listed are not well enough preserved for certain specific determination, but there is no doubt as to the genera or that the forms are of post-Portage age. In fact every form except the Edmondia is listed from the basal Chemung beds in northern Allegany County, New York. None of the forms occurs in the Portage rocks of western New York or central Pennsylvania. Indeed the appearance of such forms in the section affords the basis for separating the Chemung and the Portage. It appears from this evidence that the Bradford sand is of basal Chemung Age.

This paleontological evidence of the age of the sand is corroborated by differences in lithologic character of the beds above and below the sand and by the evident unconformable relations of the base of the sand to the beds below it. Commonly drill cuttings from the beds above the Bradford sand are decidedly calcareous; but so far as the writers know, there are no calcareous beds immediately below the sand. Detailed studies of reliable well records have shown that the Bradford sand was

is also a certain amount of soft, dark, more or less carbonaceous shale. No invertebrate fossils have been discovered in drill cuttings, but fragments of partly carbonized wood are plentiful. Fossil wood is characteristic of some horizons of the Portage at the type locality.

An excellent record of the Middle and Lower Devonian and the Silurian is shown in the log of the Derrick City deep well. This well was drilled to a depth of 5,820 feet in 1914. Several showings of oil and gas were encountered, but no commercial production was discovered below the Bradford sand. As the well was poorly located with regard to structural conditions, it should not entirely condemn the deep-sand possibilities of the field.

TABLE I

Abridged Record of Derrick City Deep Well

System	Formation	Thickness in Feet	General Character
Devonian	Chemung formation	1,200	Gray shales and sandstones; thin sandy limestones
	Portage formation	1,240	Gray sandy shales and thin fine-grained sandstones
	Hamilton shale	1,105	Soft, brown shale with a few thin sandstones
	Marcellus shale	520	Soft, brown and black shale
	Onondaga limestone	20	Hard, dark limestone
	Oriskany sandstone	40	Dark quartzite and very hard, light sandstone (showing oil)
Devonian or Silurian	Helderberg group		
	New Scotland limestone?	40	Hard, dark limestone
	Coeymans limestone?	20	Hard, dark, sandy limestone
	Keyser limestone? Tonoloway limestone?	185	Hard, dark limestone
Silurian	Cobleskill dolomite?	20	Hard, light limestone
	Bertie limestone	50	Light brown limestone
	Salina formation	410	Gypsum and salt beds; hard limestone
	Lockport dolomite	420	Hard limestone with a few dark shale beds
	Clinton formation	240	Gray sandstones and shales
	Medina formation	260	Red and white sandstones and red shale

The Chemung, Portage, Hamilton, and Marcellus are easily recognized in the log, their character and thickness being similar to those on the outcrop and in other well records. The Onondaga is only one-fifth as thick as it is at the outcrop in Niagara County, New York. Thin lenses of sandstone, at the base of the Onondaga in Niagara and Orleans coun-

OIL AND GAS HORIZONS

Horizons productive of oil or gas in the Bradford field are in descending order: the First; Chipmunk; Second; Third, or Bradford; Fourth, or Windfall, and Fourth, or Lewis Run; Fifth, or Kane of Bradford field; Kane; and Sixth, or Haskell. They are all true sandstones and are firmly cemented. The Bradford sand and those above it are in the Chemung formation; those below the Bradford have been assigned to the Portage. The Kane and Bradford are known to be marine, and the others are believed to be of similar origin.

SURFACE STRUCTURE

The Appalachian geosyncline is the major structural feature of this area. According to Butts, "The dominant structure is that of flat-lying beds dipping gently a little west of south at an average rate of about 30 feet a mile."[1] This regional dip has been confirmed at different localities by the writers. The steepest dip that has been observed on any surface bed within the Bradford field is at Lewis Run, in the southwest part, where there is an inclination of 1°45′, or at the rate of 125 feet per mile. The absence of any satisfactory key horizon in the outcropping beds has made the mapping of surface structure impractical. Where the surface structure can be determined, it has been found to conform closely with that of the Bradford sand.

There has been a marked influence of structure on drainage development in most of the area of the Bradford field. This is most readily noticed in the association of the drainage divide between Tunungwant and Potato creeks with the axis of the Simpson anticline, and of the high topography near Knapp Creek and Rock City with the crest of the Knapp Creek dome. The direction of the course of Allegheny River from Eldred, Pennsylvania, to Olean, New York, must be largely the result of the influence of structure, and there are many examples of secondary drainage development which show the effect of structural conditions.

SUBSURFACE STRUCTURE

The Bradford district is on the western edge of the belt of parallel folding characteristic of the Appalachian Mountain system. That there were other forces active in this region besides the compressional stresses originating in the area east of the field is indicated by a minor thrust fault with a north throw, striking east and west, approximately 12 miles south of the field, by the structure of the Bradford sand within the limits

[1] Charles Butts, *Report of the New York State Paleontologist* (1902), p. 968.

of the field, and by the Portville cross syncline. The resultant of these influences caused the development of a structure not common in the Appalachian region.

In general the Bradford field subsurface structure shown on the Bradford sand consists of two asymmetrical anticlines trending northeast and southwest, plunging southwest and converging on the northeast in a broad dome (Fig. 3). The closure exceeds 250 feet. The structural "highs" are characterized by their broad tops in contrast to the sharp narrow shape of the structural "lows."

In detail the main features are complicated by numerous small configurations in the upper surface of the sand. Many of these are structural but most of them are considered to be irregularities in the sea floor and, as such, to show the direction of the shore currents.

A striking relation of the subsurface structure and stratigraphy is depicted in Figure 2. The association of the thick sand area with the Knapp Creek dome is obvious. Equally striking is the thin sand condition in the Portville cross syncline. Though they also are in the lower Chemung, the productive sands in the Allegheny field northeast of Portville do not correspond with the Bradford field sands, and it is in the Portville cross syncline that the lensing-out occurs. Similarly, the Big Shanty syncline formed in an area of thin Bradford sand. A similar situation exists on the east side of the Simpson anticline. The Bradford sand thins eastward down the flank of the fold and almost disappears at the limit of production.

RESERVOIR ROCKS

LITHOLOGY

The accumulation of oil and gas in the sands above and below the Bradford seems in many places to be dependent equally upon lithology and structure. Accordingly, a brief account of their productive areas is included under this heading. Within the Bradford pool, the sands above the Bradford sand consist of uniform, medium-sized grains firmly compacted and cemented. They are ordinarily light brown to gray in color. In the northwest part of the field they consist largely of quartz sand, but in the larger part of the field they are commonly of a very shaly, calcareous, and broken character.

The First sand is logged in all parts of the field. Evidently it is part of a horizon of sandy, limy shale—a condition which explains the wide differences in thickness and stratigraphic position given for it. In limited areas in the northwest section of the field the sand consists of clean quartz grains. Elsewhere it includes much calcareous and argillaceous material.

The Second sand is more regular but is similar in extent and character to the First. However, within several thousand acres in the western parts of the field it is a tightly cemented, hard, light brown fine-grained sand. Throughout the remainder of the Bradford field it is very limy and very hard, not uncommonly being reported as the hardest stratum encountered in drilling to the Bradford sand. Many fishing jobs in drilling and difficulties in running packers are the outcome of a tight place in the hole at this horizon.

The Chipmunk sand, where present, is more uniformly of good character than the First or Second. Through the northwest part of the field it is a medium-grained, brown, medium-soft to hard sand ranging from 20 to 50 feet in thickness. Through the central and east sections it is reported as ranging from 10 to 25 feet in thickness but is composed largely of thin alternating layers of shale and hard brown sand.

Below the Bradford in the southwest part of the field is the Lewis Run, or Fourth, sand which is fine-grained and dark brown. Seemingly at the same stratigraphic position in the northeast part is the Windfall, which also is called the Fourth. It resembles the Lewis Run in texture and color. These are possibly the same horizon, but the correlation has not been established with certainty.

Successively in order under the Fourth sand are the Fifth, or Kane of the Bradford field; the Kane of the Kane field; and the Sixth, or Haskell. The Fifth is a brown to grayish sand of variable hardness but ordinarily firm. It is associated with approximately 60 feet of thin alternating sand and shale beds. It has been found extensively throughout the field but only in a small area of the northeast part, and in general in the southeast part has it been reported to contain a body of sand suitable for oil or gas accumulation.

The Kane sand of the Kane field does not correlate with the sand of the same name in the Bradford field. In fact, if it is present at all except along the south edge of the field, it has not been identified. The texture, color and composition are distinctly different from sands in this field. It is coarse grained, contains clay balls, and is dark brown.

The Sixth, or Haskell, sand resembles the Fifth in all general features except distribution. It is best developed through the central and southeastern parts of the field.

The First sand rarely was found productive. The Second sand on the west edge of the pool, southwest, west, and for a short distance north of the town of Bradford, has produced oil in commercial amounts. In the West Branch area west of Bradford, within recent years, wells have been

TABLE II

PETROLEUM RECLAMATION COMPANY'S WELL K-17, LOOKER TRACT
(Surface elevation above sea-level, 2,128 feet)

Formation	Depths to Base of Bed (Feet)	Description
	37	Residual soil
Osweyo	79	Grayish-green, yellow, and brown sands and shale
Cattaraugus	135	Gray soft sand
	145	Red shale
	156	Gray sand, yellow sand
	165	Red and gray shale
	170	Light yellow sand
	235	Interbedded red and gray shale
	257	Gray shale
	300	Gray sand
	320	Red shale. Little gray sand
	342	Red shale
	368	Gray shale
	380	Red shale
	390	Gray sand
	400	Gray shale
	429	Red shale
Chemung	650	Gray shale
	720	Mostly gray sand; little shale and shell throughout. Thin beds pink sand at 657–69 feet
	873	Interbedded pink shale, gray shale, and little gray sand
	1,046	Interbedded gray shale and gray sand, probably First sand
	1,090	Gray shale, very fossiliferous
	1,124	Interbedded gray shale, chocolate sand, and some shell
	1,139	Mostly shale, with some shell and gray sand
	1,154	Mostly fossil limestone, with little gray shale and sand
	1,175	Gray shale, with thin beds of gray sand
	1,195	Gray sand
	1,231	Gray shale
	1,263	Mostly gray shale, with thin beds of chocolate sand, Chipmunk sand
	1,278	Gray shale
	1,302	Chocolate sand, with little shale
	1,372	Gray shale
	1,396	Chocolate sand, probably Second sand
	1,466	Shale
	1,494	Interbedded chocolate and gray sand; little shale
	1,502	Shale
	1,537	Mostly chocolate sand; little shale
	1,571	Interbedded gray sand and shale. Fossil bed, near 1,573 feet
	1,614	Interbedded chocolate sand and shale
	1,702	Shale
	1,707	Shell
	1,730	Bradford sand
	1,748	Shale
	1,766	Bradford sand
Portage	1,791	Shale

completed with an initial production of 25 barrels a day from the Second sand. The Chipmunk has ranked next to the Bradford sand as a lucrative producer of oil. Unlike the Bradford, however, its productive area is limited to a few thousand acres in the northwestern part of the field. Production from it was flashy. Some wells produced as much as 250 barrels a day initially. Between Limestone and Vandalia in Cattaraugus County, New York, and beyond the limits of the Bradford pool but continuous with it, is the Chipmunk pool in which the sand of that name is the important producing horizon.

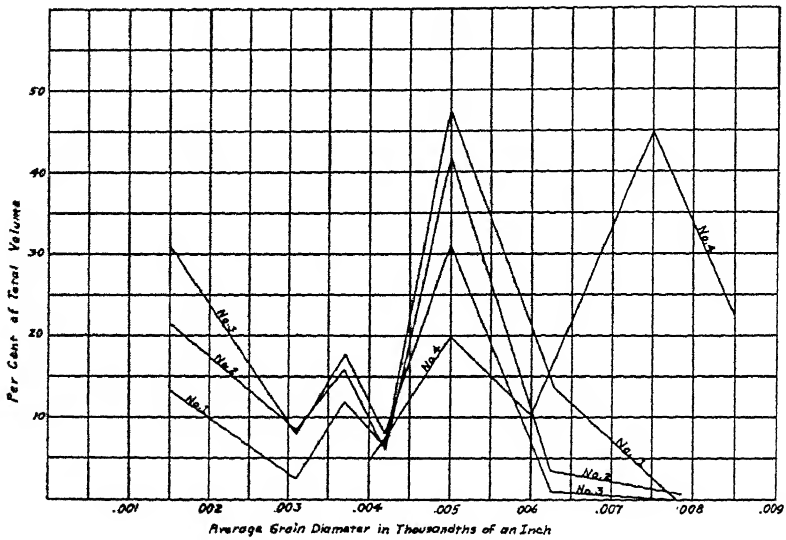

FIG. 4.—Grain-size analysis of Bradford sand from four properties of the Petroleum Reclamation Company. Nos. 1, 2, and 3, from the central part of the field; No. 4, from the vicinity of Knapp dome.

Both the Lewis Run and Windfall sands are productive of oil, the former only on the edge of the pool in the southwest part and the latter also on the edge but in the northeast part. On the axis of the Simpson anticline near Summit, Tiptop, and Duke Center the Windfall produces gas. The Kane sand of the Bradford field yields gas wells with a rock pressure of 450 pounds per square inch and a capacity ranging from 40,000 to 50,000 cubic feet per day in the extreme southern part of the field on the Simpson anticline. On the lower part of the eastern flank of the structure in this region it also produces small quantities of oil. The Haskell sand produces only gas and is productive mainly in the east-

central part of the field. The gas flow is less than that from the Kane sand, but the rock pressure varies from 450 to 800 pounds.

Bradford sand.—The Bradford sand is the principal oil-producing horizon of the Bradford pool. It is a remarkably persistent bed. Very few wells have been drilled to its horizon within the limits of the field that have not found some oil-bearing Bradford sand. It differs considerably in thickness and content of shale within the wide area in which it

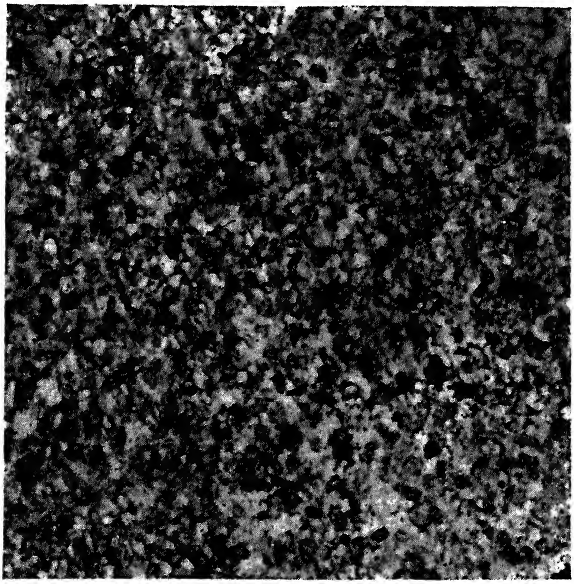

FIG. 5.—Photomicrograph of representative piece of Bradford sand from Petroleum Reclamation Company's Looker No. 145. Magnification, 20 diameters.

was deposited. The greatest thickness of sand is encountered in the northern part of the field, where it is, however, broken by many thin shale lenses (Fig. 2). It decreases in thickness toward the south, east, and west. The sand is characterized by a very uniform grain size and dark chocolate-brown color. The following description (Fig. 4) of a sample of Bradford sand has been made by Clarence Ross of the U. S. Geological Survey.

The sand grains are quartz for the most part, but there are small amounts of feldspar mica and much chert-like material. The grains are angular and interlocking, and there may have been some enlargement of the quartz. The interstitial material is not abundant but is made up of a brown mica-like clay material.[1]

[1] Clarence Ross, personal communication.

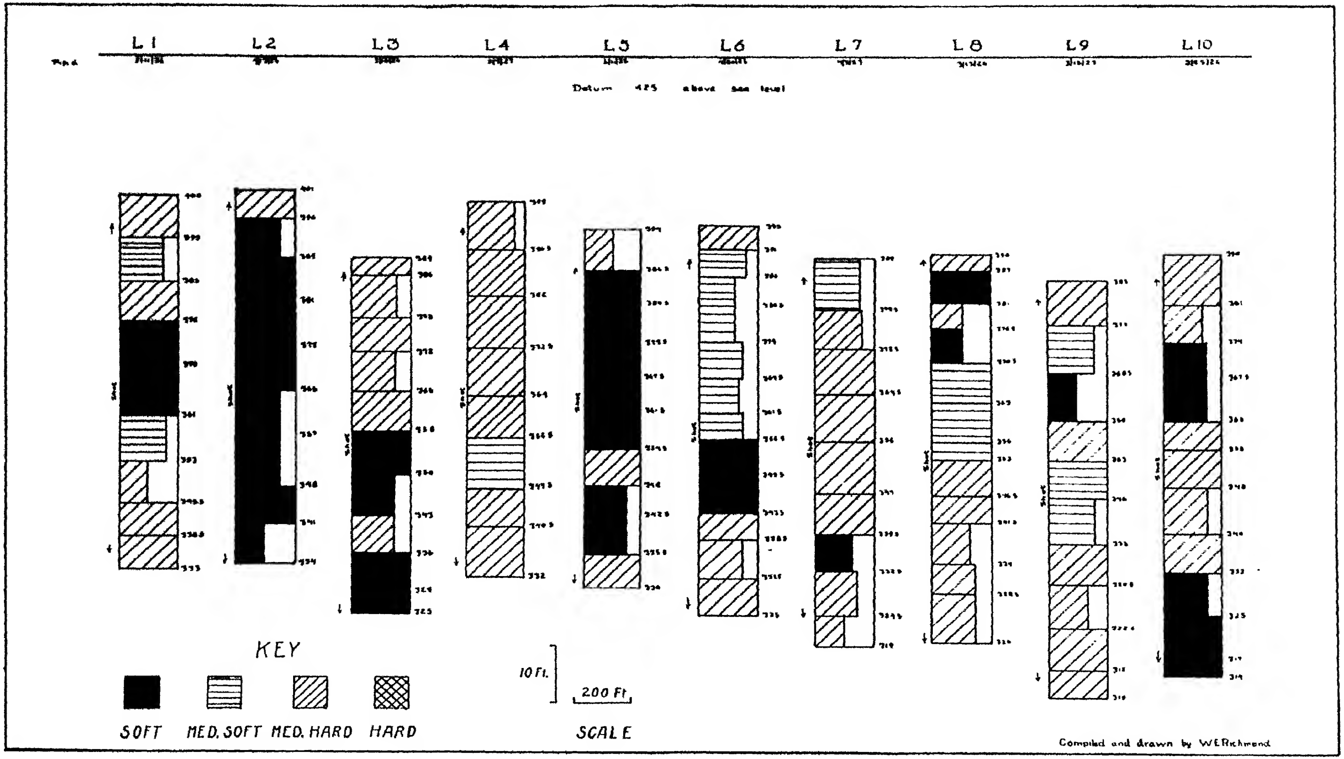

FIG. 6.—Cross section of flood line *L* on Petroleum Reclamation Company's north Looker property, Bradford field. Data from drill cuttings. Relative hardness of sand indicated by symbols; proportion of shale, by blank areas. Datum, 425 feet above sea-level.

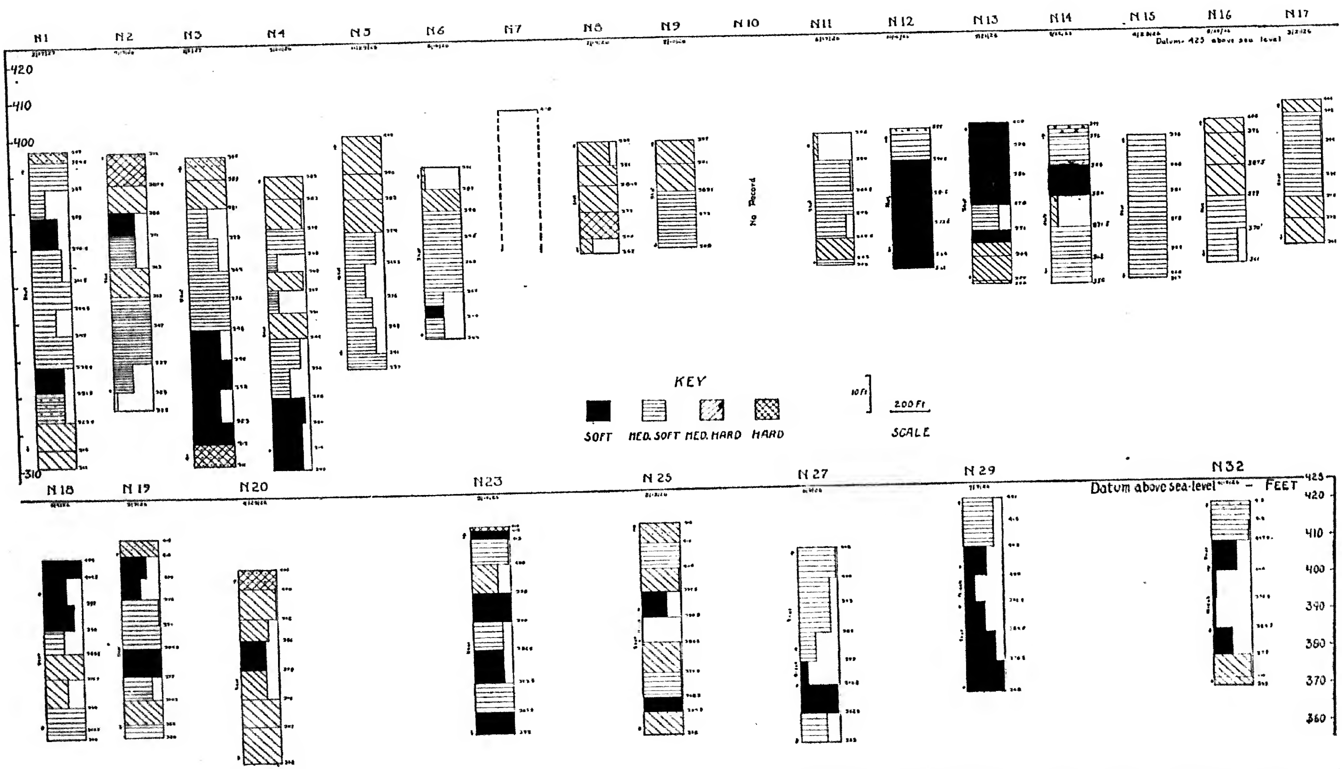

FIG. 7.—Cross section of flood line *N* on Petroleum Reclamation Company's north Looker property. Data from drill cuttings. Relative hardness of sand indicated by symbols; proportion of shale, by blank areas.

Local variations in bedding and thickness are common in some areas. This condition is well illustrated in Figures 6 and 7.

CONTINUITY

The Bradford sand extends for a considerable distance beyond the productive limits of the pool. An outline of the area in which it occurs is

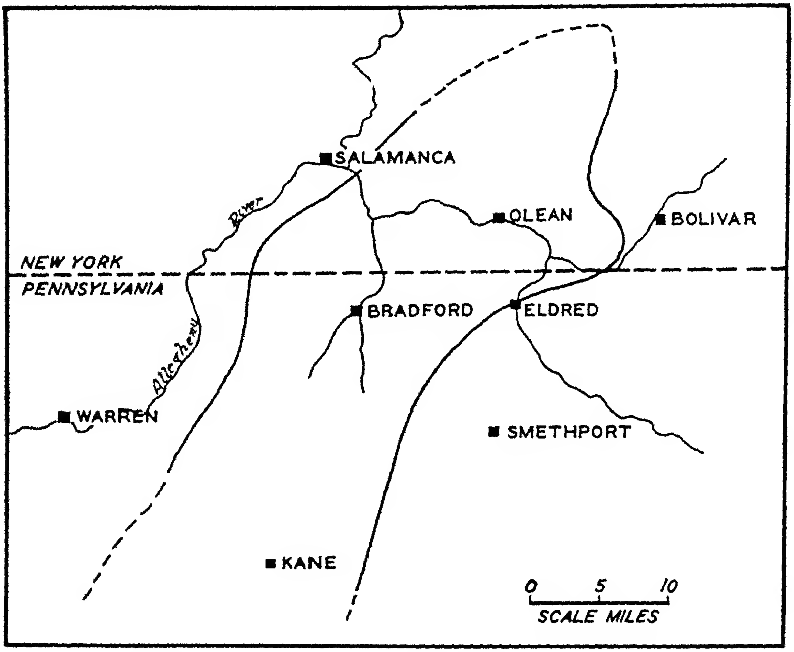

FIG. 8.—Approximate limits of Bradford sand deposition.

shown in Figure 8. In much of this area outside of the pool it either is saturated with salt water or is so tightly cemented that it contains no oil or water.

POROSITY

A determination of the porosity of the Bradford sand has been made by Melcher[1] from two diamond-drill cores, only one of which included the entire thickness of the sand. The maximum porosity is 17.3 per cent; the minimum, 11.5 per cent; and the average, approximately 15 per cent.

[1] A. F. Melcher, "The Porosity of the Bradford Sand near Custer City, Pa., and Its Relation to the Production of Oil," *U. S. Geol. Survey Memorandum for the Press 1008* (1925).

CEMENTATION

The Bradford sand is ordinarily a very hard rock. A few specimens that have been examined are somewhat friable, but most pieces require a sharp blow to break. The cementing material consists chiefly of clay and silica, which appears to be distributed fairly uniformly between the grains. The upper part of the sand is slightly calcareous, which is probably due to the proximity of a calcareous sandstone cap rock.

CAP ROCKS

Throughout most of the field, and especially in the southern part, there is a thin fossiliferous, calcareous cap rock directly above the sand. This is a very persistent horizon. Since the succeeding beds are of entirely different character, it undoubtedly represents the final stage of deposition of the Bradford sand.

ORIGIN

The outline of horizontal extent of the Bradford sand shown in Figure 8 suggests a bay origin. The very small size and angular shape of the grains indicate that it is not a beach deposit. The common occurrence of carbonized wood fragments and the marked increase in grain size from the south toward the north indicate almost a shore-line condition of deposition.

Stages of deposition of the Bradford sand may be divided into three parts: (1) the deposition of a lower series of alternating thin-bedded sandstones and shales, part of which may be non-marine; (2) a series of sand beds of fairly uniform lithology and character, although varying considerably in thickness, which mark an encroaching shore line; and (3) a calcareous cap rock which indicates a continued submergence. It is quite evident that conditions of sedimentation were continuously similar throughout a considerable area.

SOURCE ROCKS

The oil now in the Bradford sand probably originated from beds very close to it. Both the Portage and Chemung formations contain beds of carbonaceous shale which may have been the source. The relatively impermeable character of the overlying and underlying beds would effectively prevent any great vertical migration without the aid of faulting, no evidence of which has been found in the field. The high quality of the oil may be attributed to regional metamorphism, as indicated by the high carbon ratio of the coals, which averages about 57.

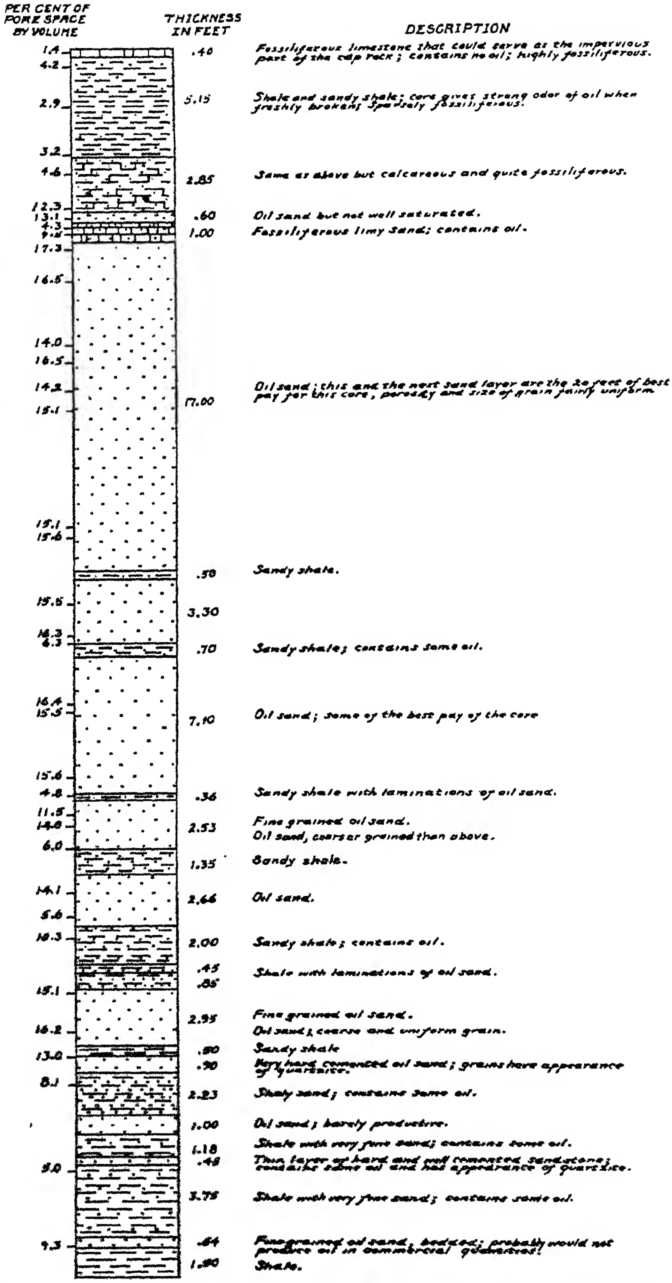

FIG. 9.—Profile showing porosity of Bradford sand from Bryner-Jackson core. After A. F. Melcher, *U. S. Geol. Survey Memorandum for the Press, 1008* (1925).

RELATION OF ACCUMULATION TO STRUCTURE

Sands productive of oil in the Bradford field, beginning with the shallowest, are the First, Second, Chipmunk, Bradford, Lewis Run, Windfall, and to a limited extent, the Fifth, or Kane. Sands mainly productive of gas are the Fifth, or Kane, and the Sixth, or Haskell.

The texture and composition of the sands other than the Bradford have been equally influential with structure in controlling the accumulation of oil or gas in those sands. Production has been procured where these features were favorable, and has been poor or wanting where they were adverse. Nevertheless, even in such irregular sand conditions the accumulation is obviously associated with structure.

The accumulation of oil in the Bradford sand has been definitely controlled by structural conditions (Fig. 10). The unproductive area which cuts through the southern part of the field approximately follows the Big Shanty syncline, and the productive area on both sides of the syncline follows the Bradford and Simpson anticlines. At the convergence of these two folds in the Knapp Creek dome and at other places along the axes of the anticlines, the upper part of the sand was a gas "pay."

There is a fairly definite oil–salt water contact on the northern, northeastern, western, and southern limits of production of the field. On the eastern edge, lithologic changes and thinning of the sand body are largely the cause for the limitation of production. Oil production extends for a greater distance down the eastern or Simpson anticline than on the western or Bradford anticline. The vertical limits of production range from an elevation of 120 feet to 550 feet above sea-level.

Migration of oil into the Bradford sand was probably a very slow process. The resistance to fluid movement through such small pores and the relatively low dip would not facilitate rapid migration. Recent work[1] in connection with studies of flood-water movement in the sand has established the fact that the sand was at one time completely saturated with salt water. Connate water, in any quantity, is found in very few places in the productive area of the field. The water used in flooding is meteoric or ground water which contains a very low concentration of dissolved salts. This water, after moving through the sand to an oil well, is pumped out as a concentrated solution, whose salinity is commonly greater than that of the connate water found on the edges of the field. The flooding process consists not only in removing oil from the sand, but also in washing it free of salts. These salts seem to be crystallized in the

[1] Paul D. Torrey, "Oil Field Waters of the Bradford Pool," *Amer. Inst. Min. Met. Eng. Tech. Pub. 38* (1927).

sand; and since the relative proportion of the several salts is similar to that found in the connate water, it is probable that they were precipitated during the period of accumulation.

Although analyses of flood waters have not been made throughout the entire area of the field, the data available indicate that the amount of salt in the sand increases away from the highest part of the structure. As oil and gas migrated into the fold, they would occupy the highest part of the structure first. A certain amount of the water of sedimentation was

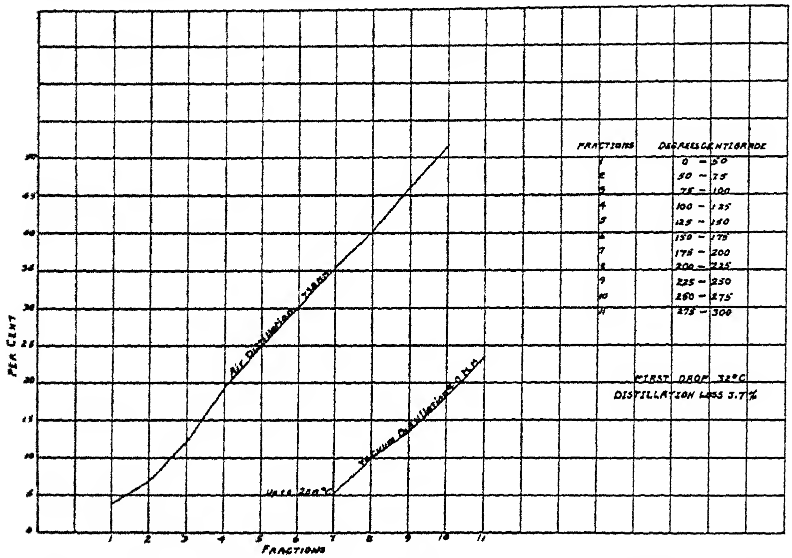

FIG. 10.—Accumulation-distillation curve of Bradford crude, Petroleum Reclamation Company's Hawkins Bryner No. 10. After U. S. Bur. of Mines.

evaporated by the gas, and a small amount of salt precipitated while the remaining water was pushed down the dip as an increasingly concentrated solution. Succeeding increments of oil and gas would have had a similar effect, and the water was ultimately removed to approximately its present position.

Wells drilled outside of the present limits of the field ordinarily find a small amount of oil which seems to be thoroughly and evenly mixed with connate water throughout the entire thickness of the sand.

OIL

Had it not been for the excellent qualities of Bradford crude, the field probably would have been almost abandoned in the period prior to the

pounds. This is subnormal, as the shallowest Bradford sand wells are 1,100 feet deep and the average for the field is 1,700 feet. It agrees, however, with the stagnant condition of the edge water. Present rock pressure ranges from 10 to 35 pounds in most of the field. Gas production is very low. Wells that make 1,000 cubic feet daily are considered good gas producers. The average is probably nearer 500 cubic feet. Natural wells have been measured that were making less than 100 cubic feet per day. There is a wide range in the ratio of oil to gas; but for the field as a whole, each barrel of oil from natural wells is accompanied by approximately 3,500 feet of gas. The gas is rich in gasoline and has an average B.T.U. value of approximately 1,800.

In the particular areas where gas accumulation had been the largest, only the upper part of the sand was a gas "pay." On the Knapp Creek dome and the Simpson anticline such areas existed, and today 18 feet (maximum) of the upper part of the sand is barren of oil. Ordinarily there was no distinct gas "pay," although a considerable volume of gas was present throughout the field.

WATER[1]

Analyses of connate water from the Bradford sand show but little variation in concentration of dissolved salts. The following analysis in Table IV can be accepted as representative of the connate water; and, for comparison, a mean of seventy-seven analyses of sea water collected by the Challenger Expedition, is given.

Since the Bradford sand is of marine origin, it may be assumed that the connate water which is present in certain areas is concentrated sea water, changed by deep-seated evaporation and possible reactions with the country rock. The large increase in the concentration of the calcium radical and the decrease in concentration of the sulphate radical are especially notable.

Although the limits of the productive area of the field were soon defined by drilling, and the position of the edge-water line was located, there is little evidence that a definite water encroachment has taken place, such as is known in some western pools. From the most reliable information obtainable, the oil-water contact has remained in a practically stationary condition during the life of the field, and at the present time there is no indication of water movement. On several edge properties, it has been found possible to remove almost all of the connate water by con-

[1] Taken in part from Paul D. Torrey, "Oil Field Waters of the Bradford Pool," *Amer. Inst. Min. Met. Eng. Tech. Pub. 38* (1927).

TABLE IV

ANALYSIS OF CONNATE WATER FROM THE BRADFORD SAND AND MEAN ANALYSIS OF 77 SAMPLES OF SEA WATER

CONSTITUENTS, IN PARTS PER MILLION

	1*	2†
Ca	13,260	420
Mg	1,940	1,300
Na	31,950	10,710
K	650	390
CO_3	0	70‡
HCO_3	0	0
SO_4	730	2,700
Cl	77,340	19,410
Br	320	0
I	10	0

REACTING VALUES, IN PER CENT

	1*	2†
Alkalies		
Na	31.1	38.6
K	0.6	0.8
Alkali earths		
Ca	14.8	1.8
Mg	3.5	8.8
Strong acids		
SO	0.7	4.6
Cl	49.3§	45.2
Weak acids		
CO_3	0	0.2
HCO_3	0	0

CHANGE IN CONCENTRATION OF DISSOLVED RADICALS FROM SEA WATER TO CONNATE WATER

Ca	×31.50
Mg	× 1.49
Na	× 2.97
K	× 1.66
SO_4	× 0.27
Cl	× 3.98§

* Brine from Bradford sand, collected May 4, 1926, while well was being pumped, from Associated Producers Company's Stover No. 23. This well produces a considerable amount of salt water. It is located in the extreme southern part of the field. Analyzed by E. A. Swedenborg.

† Mean of 77 analyses of sea water collected by the Challenger Expedition.

‡ Reported and calculated as CO_3, but probably in part HCO_3.

§ Includes Br and I.

tinued pumping, and, although large volumes of salt water are known to exist in the vicinity, there is no evidence that water is moving in to replace that which has been previously removed. It is probable that there are a number of contributing factors responsible for this rather exceptional condition. The only possible outcrop of the Bradford sand is on the north. It cannot be recognized in well records from Warren County, as has been pointed out by Butts;[1] and it is known to thin out a short distance east of the present boundaries of the field. The basal beds of the Chemung formation, in New York, contain several sandstones which are in many ways similar to the Bradford; but since a definite correlation between them cannot be made, it seems probable that the sand does not crop out; consequently, it cannot directly receive additional water from the surface.

Even if one of the basal Chemung sandstones, on the outcrop, is the Bradford, there is considerable question whether there would be any great artesian movement, for a distance of approximately 40 miles, through sandstones of low permeability such as characterize the lower part of this formation, with a regional dip of only 30–40 feet to the mile. The resistance of the sand to fluid movement within the field is so great that standard flooding practice requires a spacing of wells from 100 to 200 feet apart. Under a wider spacing pattern, the movement of the flood water is so slow that the greater time required to deplete a given area makes the average flood unprofitable. It is believed this evidence adequately accounts for the stagnant condition of the connate water which partly surrounds the productive area of the Bradford sand.

OIL AND GAS PRODUCTION

DRILLING

Development costs are exceptionally low. A single string of casing is used for shutting off ground water, the average lower limit of which is approximately 350 feet. Below that the hole is open, and no trouble with caving is experienced. This is accounted for by the fairly firm, brittle character of the strata with the saving feature of "mudding up" readily. Drilling is entirely with standard tools, and progress is rapid. It is customary for a drilling outfit to complete a well a month including the time for moving and rigging up. Contract price varies from $0.95 to $1.00 per foot, which covers moving expense, fuel, and water.

[1] *Op. cit.*

PRODUCTION METHODS

The Bradford field has become widely known in recent years because of the signal success attached to the water-flooding method of increasing production. Little attention has been paid to the natural production of the field. On the 85,000 acres in the productive area of the Bradford sand there are approximately 25,000 producing wells yielding a total of 11,000 barrels a day. Approximately 5,000 of these are affected by flood pressure and are estimated to be yielding more than 7,500 barrels a day. The 20,000 natural producers are considered to have an average daily production of $\frac{1}{8}$ barrel, or a total daily production of 2,500 barrels. It will be seen that a substantial part of the present production is natural. Most of the natural wells have been producing since the early eighties. Pumping troubles of course are at a minimum, the chief sources being paraffining, "floating" sand, and extreme weather conditions.

The discovery that putting water under pressure into the sand was a means of greatly increasing production and was not wholly harmful is supposed to have been made accidentally. Presumably practiced unintentionally at first, the process certainly has been in use for thirty years, and probably for a longer time. Practice and results from flooding, together with characteristics of water floods, have been set forth by Umpleby.[1]

The original method was circle flooding, in which a central well is used as a water intake and a surrounding row of wells pumped as producers. As the flood spreads outward, a second, larger circle of wells is drilled and pumped and the first circle of wells used as water intakes. This method was much improved by the adoption of a straight-line systematic plan in which, to start a flood, a central row of wells is drilled as water intakes and a row of wells on each side, staggered with respect to the water intakes, used as producers. Successive additional rows of producers are drilled, and the old rows converted into intakes as the forward movement of the flood requires additional development; but the staggered, evenly spaced system of well locations is retained.

Other improvements in technological methods that are being tried by operators in the Bradford field and the Allegheny fields of New York are: (1) a greater spacing between the rows of wells in systematic floods, (2) the boundary flood, (3) the four-way, or "five-spot," flood, (4) introducing the water under greater pressure by means of force pumps, (5) the use of

[1] Joseph B. Umpleby, "Increasing the Extraction of Oil by Water Flooding," *Amer. Inst. Min. Met. Eng., Petroleum Division* (1926), pp. 112–29.

various solutions for freeing the oil from the sand, (6) combined intensive air- or gas-flooding and water-flooding, and (7) air- or gas-flooding alone.

1. Spreading the well spacing in systematic floods is an attempt to increase profits by reducing development and operation costs without an equal decrease in production obtained. Under conditions of open, hence more rapidly flooding, sand, it is logical and seems to have succeeded. In slower-flooding areas it promises to accomplish the desired result, but generally definite success cannot be claimed until a longer time has elapsed from its inception. The systematic method began with a spacing of approximately 100 feet between rows of wells and 200 feet between wells in each row. The exact distances were gauged to make the spacing fit property dimensions. The spacing in each row must be continued if the wells are to be staggered, but the distance between rows can be changed much more readily. A width between rows of as much as 120 feet is now common, and in some places a greater width is used. There are no known guides to correct spacing other than the recovery per well and the rapidity of flood movement. The judgment of the operator guided by the particular conditions in any flood must decide the distances used. It is too early for a comparison of the shorter and longer spacings. However, by following the plan of varying the well spacing, the observant operator should be able to learn for each flood the grid that yields the most profit.

2. In a boundary flood, alternate water and oil wells are drilled around the boundary of the property. Wells are spaced approximately 100 feet apart, with the result that the effects of the flood appear at the oil wells within three months and the total production is obtained within fifteen months. In this time the cost of the oil well and a part of the cost of the water intakes is returned. The production secured comes from the parts of the flood in which oil is most likely to be trapped. The plan has been most successfully used as an aid in financing the development of the flood.

3. The four-way, or "five-spot," plan requires the division of the property into small squares at each corner of which a water intake is drilled. An oil well is then drilled in the center of each square, and the flood moves from four directions toward each oil well. Spacings used for this plan by different operators have ranged from 260 to 528 feet between water intakes. A large capital investment before any returns are forthcoming and the danger of trapping oil because of open streaks or other irregularities in the sand body are objections to the "five-spot" method of development. At this time, however, the production results that are being obtained indicate that the second hazard is not disastrous.

4. The addition of water pressure above that of the natural hydro-

static head from the ground-water table to the sand is being used with success principally in the Allentown and Richburg sections of the Allegany field, though in a few places it has resulted satisfactorily in the Bradford field also. The best increase that has attended its application was in connection with a systematic flood, the wells of which seemingly were nearly watered out. Raising the water pressure raised the oil production from 3 to 20 barrels without seriously increasing the amount of water production. Added pressures are applied principally in tight-sand areas. In looser sand they ordinarily increase the flow of water markedly, with little or no oil increase.

5. Much attention has been given to the possibility of improving oil extraction by introducing solutions into the water intakes. Soda ash has been used in large quantities by some of the operators, and other substances have been tried. The desired result is to free from the sand that part of the remaining oil, estimated at a maximum of 35,000 barrels an acre, which is retained largely by adhesion.[1] When the oil is freed, it should be possible to push with water a reasonable percentage of it into the oil wells, thereby increasing the recovery per acre. The process promises much, but to date there is only one example, and it doubtful, of a well that seems to have yielded more oil than would have been secured by normal water-flooding. This also is the only producing well from which any soda solution has been pumped. The well is the Pressure Oil Company's Artley No. 4, operated by William Purple and associates. Harmful effects from crystallization of the soda ash resulted in a few places where highly concentrated solution was used or introduced before being cooled. The results from the use of other solutions have been negative. All efforts to increase recovery by the use of chemicals are still in the experimental stage.

6. Excellent increases in production have come from introducing air or gas in front of a water flood. Several wells making 3–4 barrels by water flooding have increased to 12–15 barrels after the introduction of air. The air or gas pressures used varied from 125 to 425 pounds, depending principally on the tightness of the sand. In most parts of the field the higher pressures are necessary.

7. Air-flooding, removed from water floods, is giving good results in territory where the sand is exceptionally permeable. Where the sand is tighter, higher pressures must be used, and the results are much slower in appearing. Pressures as low as 80 pounds are sufficient locally, but in most places 400–425 pounds are required.

[1] A. F. Melcher, *U. S. Geol. Survey Memorandum for the Press, 1008* (1925).

PRODUCTION

Initial production of wells in the Bradford sand probably did not average more than 50 barrels a day, although locally wells producing as much as 1,000 barrels were found. It is of interest that water travels more

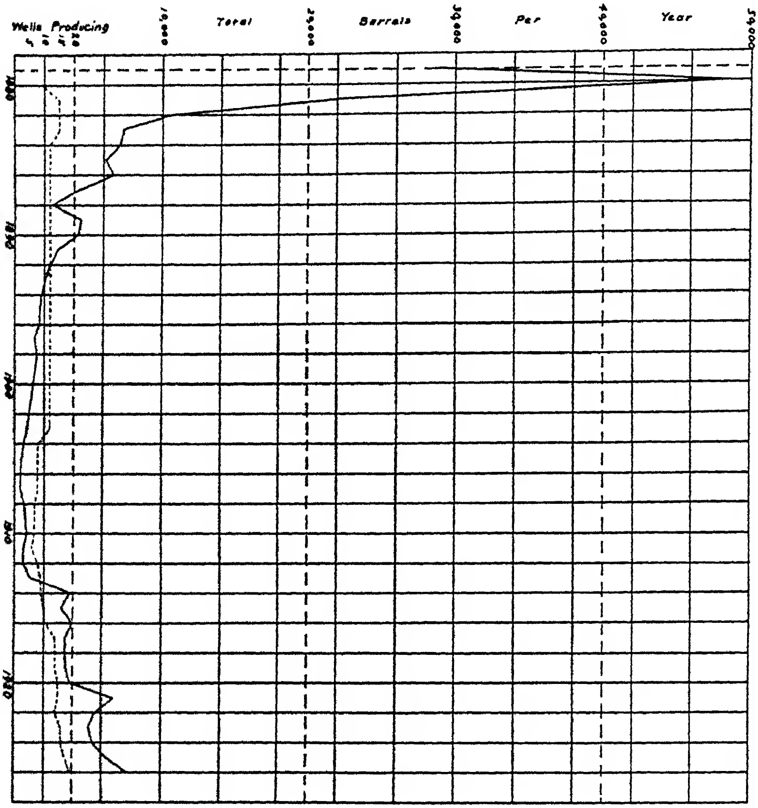

FIG. 11.—Production curve of typical Bradford sand property, Bradford field.

rapidly in areas of largest initial production, seeming to indicate that freedom of movement in the sand rather than differences in pressure or amount of gas controlled initial production (Fig. 11).

To the end of 1926 the Bradford field is estimated to have produced 257,000,000 barrels of oil. Present production is 4,000,000 barrels a year. The low year in production was 1907, when less than 1,500,000 barrels were produced. More than the 2,500,000 barrels a year of increase can

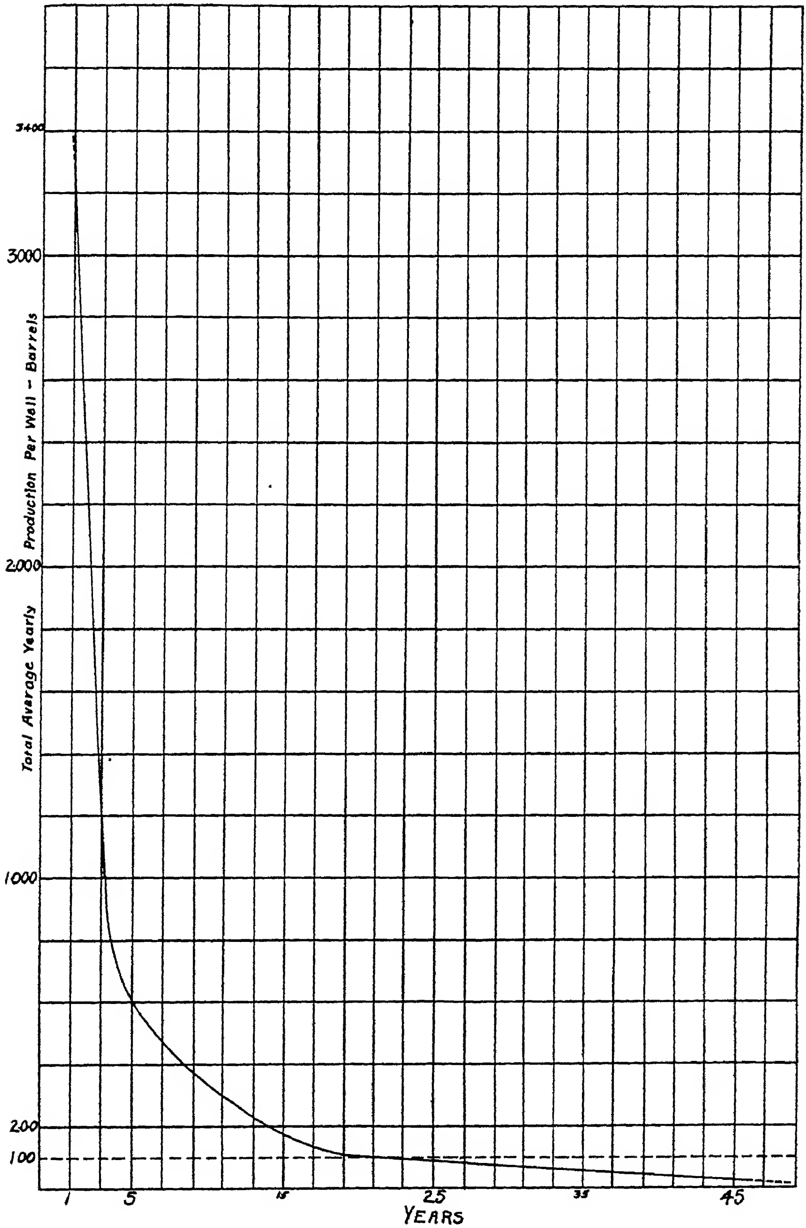

FIG. 12.—Average decline curve for seven properties, Bradford field.

be attributed to water-flooding. Approximately 13,500 acres ($10\frac{1}{2}$ warrants or 21 square miles) are under water flooding, of which fully two-thirds, or 9,000 acres, are watered out. It is safe to say that under present methods and present floods the field has fifty years of active life ahead of it, and it is probable that it will still be producing at the end of seventy-five years (Fig. 12). Nevertheless, rows of water intakes, which, placed end to end, would extend for miles, have been drilled within the last five years, and new rows that would nearly equal them in length are now being drilled. If continued, this rate of intensive new development will greatly shorten the life of the field under present flooding methods.

SCENERY HILL GAS FIELD, WASHINGTON COUNTY, PENNSYLVANIA[1]

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Pittsburgh, Pennsylvania

ABSTRACT

Scenery Hill, a small village in West Bethlehem Township, Washington County, Pennsylvania, 25 miles southeast of the famous McKeesport field, was the scene of unusual activity in the spring of 1927, when the first gas well was completed in that field. Since that time thirty-six wells, sixteen of which were dry holes, have been drilled within a radius of 1 mile.

Local domes located on a plunging syncline afforded an ideal condition for the segregation of gas, oil, and water. Unfavorable sand conditions caused many dry holes.

Twenty wells produced 1,500,000,000 cubic feet of gas, with original rock pressures varying from 1,000 to 1,200 pounds. Production was largely from the Fifth sand. This compares on a small scale with the McKeesport field production of 22,000,000,000 cubic feet of gas from approximately 800 wells.

Production reached its peak during November, 1927, when fifteen wells produced 454,600,000 cubic feet of gas. By August, 1928, there were only four producing wells, sixteen having been abandoned. The four active wells produced only 3,556,000 cubic feet of gas in July, 1928, these being operated on a vacuum.

INTRODUCTION

Scenery Hill is a small village in West Bethlehem Township, Washington County, Pennsylvania, on the National Highway, 3 miles west of Beallsville, 14 miles east of Washington, and 25 miles southwest of McKeesport.

Wells had been drilled in the vicinity of Scenery Hill thirty years ago, but not until May, 1927, was Scenery Hill known as a gas field. The development in this field has been termed that of "a little McKeesport field," which was developed in the latter part of 1919. Scenery Hill was also a town-lot field. The McKeesport gas field, however, produced about 22,000,000,000 cubic feet of gas, and the estimated production at Scenery Hill field was 1,500,000,000 cubic feet of gas.

The development of the McKeesport gas field, in which approximately $35,000,000 were lost, was soon forgotten, and history was repeated at Scenery Hill, only on a smaller scale.

[1] Manuscript received by the editor, August 13, 1928.

[2] Geologist and engineer, The People's Natural Gas Company.

ACKNOWLEDGMENTS

The writer wishes to acknowledge thanks to E. E. Roth, geologist, Manufacturers Light and Heat Company, and to J. H. Newlon, geologist, Philadelphia Company, for assisting in comparing data, as well as offering suggestions and criticisms in the preparation of this article.

STRATIGRAPHY

The principal producing horizon in the Scenery Hill gas field is the Fifth sand, which is at the base of the Catskill formation in the Devonian system; however, small quantities of gas were obtained from the Big Injun, Gantz, and Gordon Stray sands. The outcropping horizons are those of the Dunkard series in the Corniferous system. Table I shows the comparisons of the horizons penetrated in the vicinity of Scenery Hill. Measurements are shown in feet above or below the Pittsburgh coal horizon.

Dunkard formation.—The Dunkard formation of the Pittsburgh series of the Carboniferous system has been so eroded that only 520 feet of the lower part of this formation is visible.

Monongahela formation.—The Monongahela formation lies just beneath the Dunkard formation, the base of which is distinguished by the Pittsburgh coal bed. This coal is an important marker in the oil and gas fields of Pennsylvania, and most sand horizons and production are referred to it for identification as being so many feet below the Pittsburgh coal bed. The Monongahela formation in this vicinity has a thickness of approximately 400 feet, made up primarily of shale, sand, sandstone, and several coal seams.

Conemaugh formation.—The Conemaugh formation, next beneath the Monongahela formation, is composed of gray-brown micaceous sandstone, some of which carries quartz pebbles. Thin coal seams and lime horizons are also found in the Conemaugh formation. Considerable gas has been found in Pennsylvania in the Murphy sand, Little Dunkard (First Cow Run sand or Buffalo sand) and Big Dunkard (Mahoning) sand.

Allegheny formation.—The Allegheny formation lies immediately under the Conemaugh formation and has a thickness of 110 feet. Many important coal horizons are found within this formation. The First gas sand is a prolific producing sand in the southwestern part of Pennsylvania.

Beaver River formation (Pottsville series).—The Beaver River formation next below the Allegheny is the last formation in the Pennsylvanian subsystem of the Carboniferous system. It has a thickness of 320 feet. It contains the First salt sand, Second salt sand, Third salt sand, and

TABLE I

System	Subsystem	Series	Formation	Name of Formation	Feet Above and Below Pittsburgh Coal: Top	Bottom
Carboniferous	Pennsylvanian	Pittsburgh	Dunkard	Waynesburg "A" coal	390	
			Monongahela	Waynesburg coal	335	
				Uniontown coal	275	
				Mapletown coal	120	
				Redstone coal	70	
				Pittsburgh coal	0	
			Conemaugh	Murphy sand	180	230
				Bakerstown coal	380	
				Little Dunkard sand	385	440
				Mahoning coal	520	
				Big Dunkard sand	525	600
			Allegheny	Upper Freeport coal	605	
				Lower Freeport coal	650	
				Upper Kittanning coal	705	
				Middle Kittanning coal	745	
				Lower Kittanning coal	785	
				First Gas sand	785	805
		Pottsville	Beaver River	First salt sand	810	880
				Second salt sand	890	1,000
				Third salt sand	1,005	1,075
				Maxton sand	1,080	1,130
	Mississippian	Mauch Chunk	Mauch Chunk	Mauch Chunk red shales	1,120	1,130
				Little lime	1,130	1,145
				Pencil Cave	1,145	1,155
		Pocono	Burgoon	Big lime	1,155	1,215
				Big Injun sand	1,215	1,480
			Cuyahoga	Squaw sand	1,520	1,655
				Patton shale (red)	1,675	1,725
			Berea	Second gas sand	1,780	1,810
				Murrysville sand (Berea)	1,855	1,910
Devonian		Upper	Hundred-Foot	Gantz sand	1,975	2,025
				Fifty-foot sand	2,035	2,070
				Thirty-foot sand	2,110	2,130
			Catskill	Snee sand	2,145	2,160
				Gordon Stray sand	2,185	2,210
				Gordon sand	2,230	2,260
				Fourth sand	2,285	2,305
				Fifth sand	2,340	2,350
		Middle	Chemung	Bayard sand	2,435	2,450
				Bayard Stray sand	2,500	2,510
				Elizabeth sand	2,530	2,540
				Speechley sand	3,270	3,290

Maxton sand, all of which are productive in some parts of Pennsylvania. These sands ordinarily contain a large amount of salt water, and it is common practice, when drilling to deeper horizons, to case through them.

Mauch Chunk.—The Mauch Chunk series separates the Pennsylvanian system from the Mississippian system. This group consists of red, green, and black shales, with a limestone, known as "Little lime." The bottom of the Pencil Cave forms the base of this series.

Burgoon formation.—The Burgoon formation next below the Mauch Chunk formation is composed of the Big lime and Big Injun sands, and comprises an interval of approximately 320 feet. The Big lime, as correlated by the drillers, is generally known as the "Greenbrier limestone." The Big lime is productive of gas in southern West Virginia, but nowhere in Pennsylvania does it produce either oil or gas. The Big Injun sand is one of the most prolific gas-bearing horizons within the state of Pennsylvania. It has an average thickness of 250 feet.

Cuyahoga formation (Pocono system).—The Cuyahoga formation, which is below the Burgoon formation, is composed of the Squaw (Weir) sand and is productive in parts of Pennsylvania.

Berea formation.—The Berea formation, next below the Cuyahoga formation, constitutes an interval of approximately 200 feet and is composed of the Second gas sand and the Murrysville or Berea sand, both of which are productive within the state of Pennsylvania. The Berea formation forms the base of the Carboniferous system, and the Gantz sand is the top of the Devonian system. The Gantz and Fifty-foot sands form the Hundred-foot sand. Both are productive in Pennsylvania, and the Gantz sand is productive at Scenery Hill. The Thirty-foot sand comes immediately below the Fifty-foot sand, and is productive throughout a larger part of the state. The Berea sand crops out at Corry, Pennsylvania, approximately 150 miles north of Scenery Hill.

Catskill formation.—The Catskill formation, which is the beginning of the red beds, has an interval of 340 feet and is composed of the Snee sand, Gordon Stray sand, Gordon sand, Fourth sand, and Fifth sand, all of which are productive within the state. The Fifth sand is at the base of the red beds and is a very thin sand. In this vicinity it scarcely exceeds 15 feet in thickness.

Chemung formation.—The Chemung formation lies next below the Catskill formation. It has a thickness of approximately 1,800 feet. Much of the production from Pennsylvania is obtained from this group of sands; namely, Bayard Stray, Elizabeth sand, Warren sand, Speechley and

Tiona sands, Balltown sand, Sheffield sand, and Bradford sand. No production at Scenery Hill has been found below the Fifth sand; however, approximately 2 miles northwest, production has been obtained from the Speechley sand of this same formation.

STRUCTURE

The relation of the oil and gas to structure in the Appalachian field has been doubted by many well-known operators. This pool seems to be an ideal situation to clarify some of the erroneous opinions, which are seemingly fixed in the minds of many of the most prominent oil and gas operators. Scenery Hill is located in the Waynesburg syncline; however, it is a considerable distance from the basin or low point which is south and west of the town of Waynesburg in Franklin Township, Greene County, at which point the Pittsburgh coal has an elevation of 350 feet above sea-level. This syncline extends northeast and southwest, Scenery Hill being located 16 miles northeast, out of the basin, or at a point where the Pittsburgh coal has an elevation of approximately 640 feet above sea-level. The accompanying structure map (Fig. 1), drawn on the Pittsburgh coal horizons, shows the local structure in the vicinity of this gas field. It is shown on the structure map that the production comes from a small dome which affords an ideal place for the accumulation of natural gas. The intervals from the Pittsburgh coal to the various horizons (Fig. 1) are so regular that the subsurface structure would parallel that drawn upon the Pittsburgh coal horizon; and since the Pittsburgh coal is recognized by all drillers, it affords an ideal marker upon which to base the structure. The surface elevation in the vicinity of Scenery Hill ranges from 1,000 feet to 1,486 feet above sea-level; therefore, the Pittsburgh coal horizon is well beneath the surface at all points (the major unconformity in this area is between the Pottsville [Pennsylvanian] and the Mauch Chunk [Mississippian]).

Approximately 2½ miles southwest of Scenery Hill oil has been found in the Fifth sand. The production of some of the wells varied from 10 to 20 barrels a day. The structural elevation on the Pittsburgh coal bed at this point is 587 feet above sea-level; the high point on the local dome at Scenery Hill is 642 feet. The gas is at an elevation approximately 55 feet higher than where oil was encountered.

The production from the Scenery Hill field is termed "synclinal," but it must be remembered that in the Appalachian field there are plunging synclines and anticlines; therefore, before conclusions are reached, a careful study must be made to see if the production is low in the syncline or

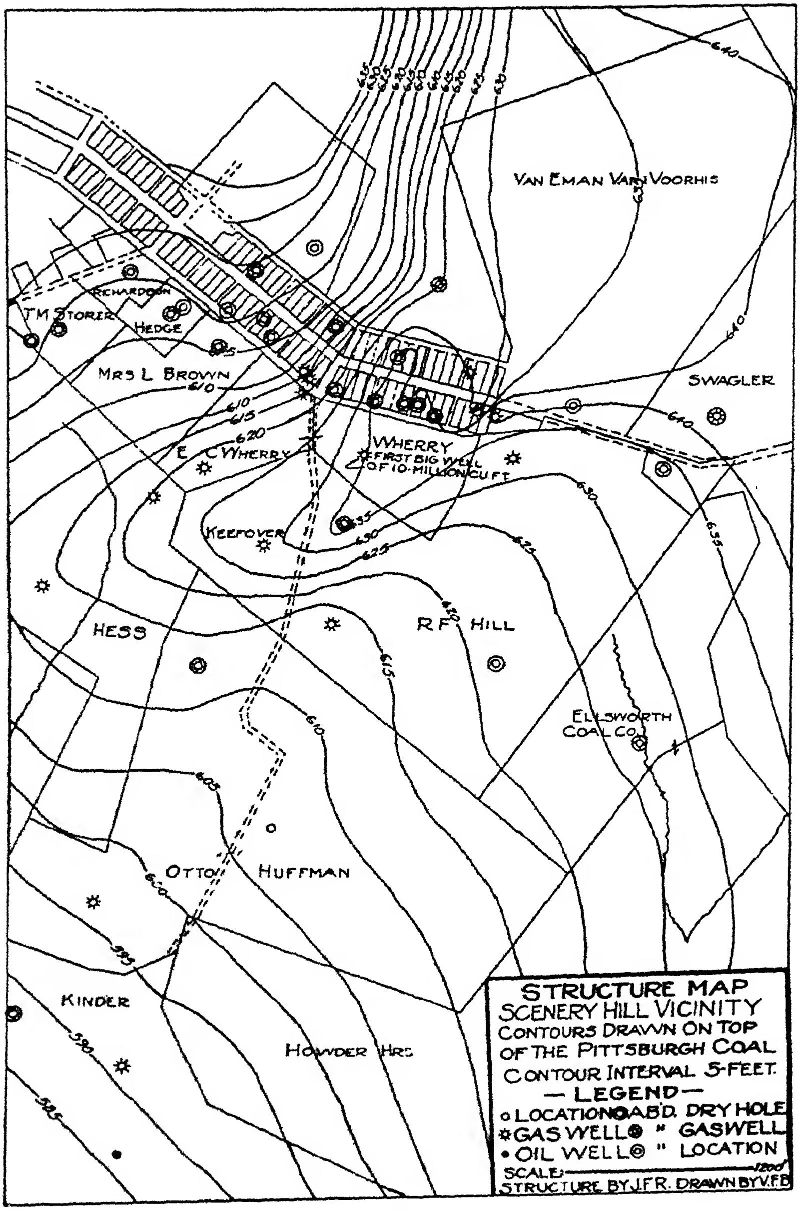

FIG. 1.—Structure of Scenery Hill gas field, contoured on top of Pittsburgh coal. Contour interval, 5 feet. Scale in feet.

basin or if it is high on a rising syncline. That is the condition here; and although the production is in the syncline, the structural elevation is higher than points on the adjacent anticlines where production is found.

The famous McKeesport field was located on a flat nose of the Murrysville anticline. The elevation of the Pittsburgh coal horizon at this place ranges from 1,050 to 1,250 feet above sea-level.

SANDS

The principal producing sandstones in Scenery Hill, together with most of the other sandstones recorded in Figure 1, are very persistent through the larger part of western Pennsylvania.

The Speechley sand has been the lowest producing horizon in the extreme southwestern part of the state. Just north and east of Scenery Hill the Bradford sand (base of the Chemung formation) becomes productive. This horizon is approximately 800 feet below the Speechley sand. In the northern part of the state, the Kane sand (Portage formation) is productive. This horizon is approximately 1,200 feet below the Speechley sand.

PRODUCTION

The production from the Scenery Hill gas field was almost entirely from the Fifth sand. The first well in the field was completed in May, 1927. Since that time thirty-six wells have been drilled within a radius of 1 mile, sixteen of which were dry holes. Of the twenty gas wells which have been producing in this field, all but four are now abandoned. The original rock pressure at some of the wells varied from 1,000 to 1,200 pounds. Line pressures formerly were as high as 500 and 600 pounds but are now being operated on a vacuum. The production by months and the well data from this field are shown in Table II.

The Scenery Hill gas field reached its peak in November, 1927. During this month it produced 454,600,000 cubic feet of gas, at which time fifteen producing wells were in the line and six dry holes had been completed.

The total production from the field to August, 1928, was 1,460,734,000 cubic feet of gas.

Scenery Hill is so located that practically no gas was wasted, as it required only a short time for the companies to supply pipe-line facilities. The local field is now almost exhausted, and the prospects are that a Speechley sand gas field may be developed north and west of this field.

CONCLUSIONS

In the writer's opinion the structural condition caused the accumulation of gas at this place; however, the sand condition, being so hard in one locality and a little more porous in others, accounts for the good wells in one place and the dry ones in another. As shown on the structure map, it was not uncommon to have a very good well on one lot and a dry hole on the adjacent lot.

TABLE II

MONTHLY PRODUCTION, SCENERY HILL FIELD

Year	Months	Cubic Feet	No. of Producing Wells	No. of Abandoned Gas Wells	No. of Dry Holes
1927 . . .	May	25,459,000	1	0	0
	June	37,729,000	1	0	0
	July	41,116,000	1	0	0
	August	134,408,000	3	0	0
	September	175,050,000	4	0	0
	October	195,710,000	9	0	3
	November	454,600,000	15	0	6
	December	213,351,000	14	1	11
1928.	January	81,176,000	11	5	13
	February	41,046,000	10	10	15
	March	30,146,000	10	10	16
	April	20,444,000	10	10	16
	May	4,702,000	9	11	16
	June	2,241,000	6	14	16
	July	3,556,000	4	16	16
Total.	. . . .	1,460,734,000	. . . .	. . . .	. . . .

This field illustrates synclinal production of gas, but it is found on a plunging anticline. Oil is found in the same syncline but lower on the structure. Water is also found below the oil. Local domes on the syncline afford ideal conditions for the segregation of the water, oil, and gas.

Most sands in this territory are very extensive and uniform, the tight texture of the sands being the cause for most of the dry holes drilled on otherwise favorable structure.

WEST COLUMBIA SALT DOME AND OIL FIELD, BRAZORIA COUNTY, TEXAS[1]

D. P. CARLTON[2]
Houston, Texas

ABSTRACT

Oil accumulation on salt domes is either in super-cap sands, cap rock, or lateral sands. West Columbia is an example of a salt-dome oil field which produces only from lateral sands. One 20-acre lease has produced 620,000 barrels an acre in eight years. The Texas Company's Abrams No. 1 was completed on July 20, 1920, and for six weeks flowed at the average rate of 26,500 barrels per day of pipe-line oil.

INTRODUCTION

The West Columbia salt dome has associated with it one of the principal oil fields of the coastal region of Texas and Louisiana. The dome lies in Brazoria County, west of Brazos River, about 50 miles southwest of Houston and 25 miles from the Gulf of Mexico. It is accessible from Houston by automobile or by train (the International and Great Northern Railroad) to Columbia, 3 miles southeast of the field. The dome at West Columbia is approximately in the center of a group of sixteen domes located in Matagorda, Fort Bend, Wharton, Harris, and Brazoria counties. It is the only oil producer of importance in the group, eight of which were recently discovered and are comparatively undeveloped. As a producer of oil, it ranked fourth among Texas salt-dome fields at the close of 1927 (Fig. 1).

ACKNOWLEDGMENTS

The writer wishes to acknowledge his indebtedness to H. E. Minor, of the Gulf Production Company, and to Ray F. Baker, of The Texas Company, for the use of samples and well records; to Miss A. C. Ellisor, of the Humble Oil and Refining Company, for paleontologic determination of the samples; to G. M. Dougherty, who assisted in the preparation of the illustrations; and to others[3] who have offered suggestions and assisted in the proofreading of the copy.

[1] Manuscript received by the editor, November 12, 1928.

[2] Humble Oil and Refining Company.

[3] D. C. Barton, "The West Columbia Oil Field, Brazoria County, Texas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 5, No. 2 (March–April, 1921), pp. 212–51.

HISTORY

Early in 1901, after the completion of large wells at Spindletop salt dome in Jefferson County, Texas, development was begun at West Columbia, or Kaiser's Mound. The presence of a slight topographic mound with a central, swampy basin, gas seeps, oil showings, and paraffin-dirt beds had attracted attention to the locality. Several unimportant shallow wells were drilled during the first fifteen years of development; however, no

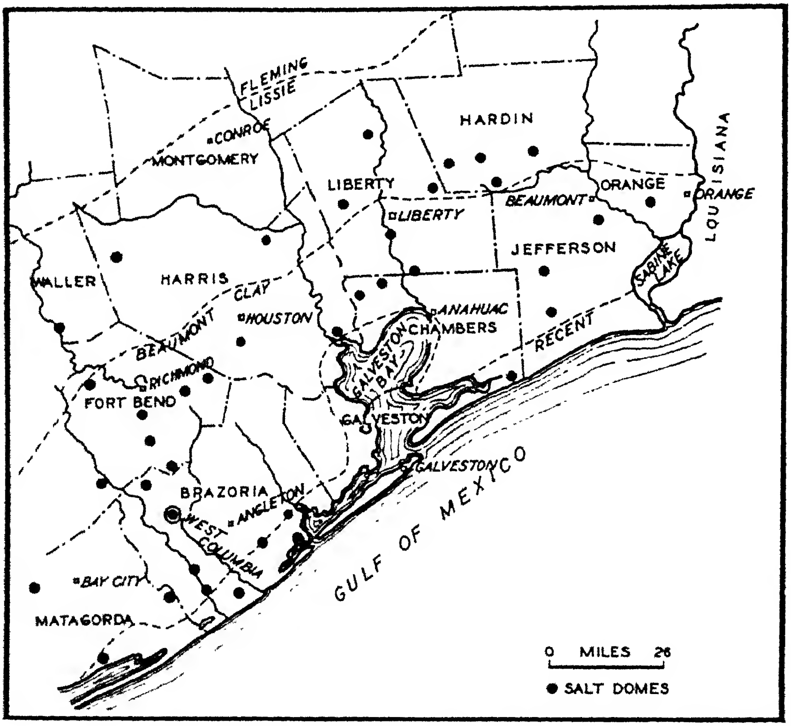

FIG. 1.—Location of salt domes in southeastern Texas.

production of importance, such as at Spindletop, was obtained from these cap-rock wells. In 1917 the first deep-sand well was completed on the Tyndall-Wyoming lease on the northeast side of the dome. In the winter of 1918 better deep-sand wells were completed, and in January, 1919, The Texas Company completed its Arnold No. 2 with an initial production of 6,500 barrels per day.

At the end of 1919 the producing area was delimited on the north, south, and west. Late in the summer of 1920 the field was extended to-

ward the east by the completion of the W. C. Hogg wells of the Gulf Production Company. Since the end of 1920 no important developments have taken place.

The peak of production for the field was in 1921, during which year 12,500,000 barrels of oil were produced.[1]

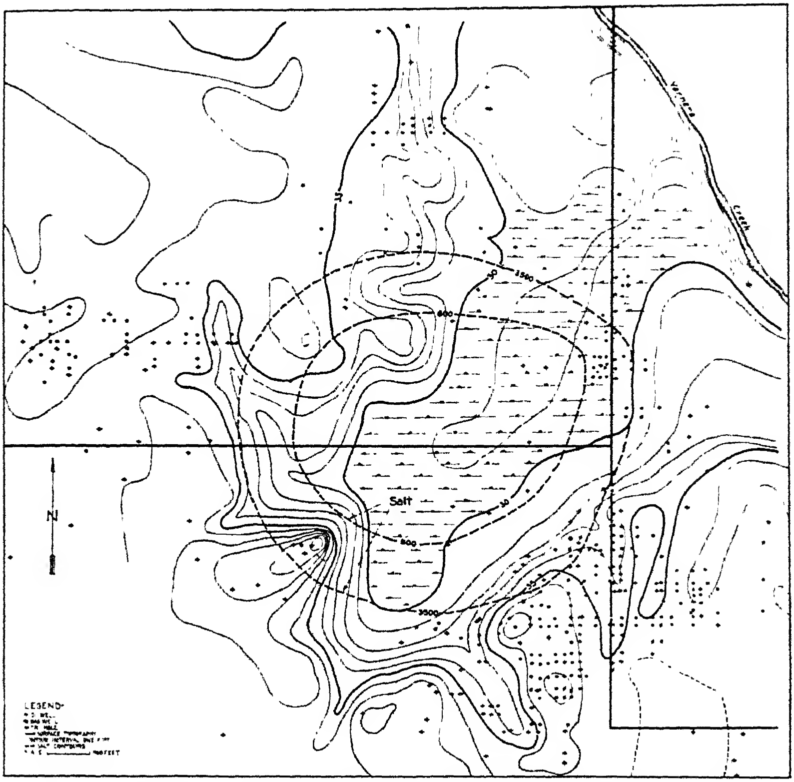

FIG. 2.—Topography of West Columbia, showing position of salt with respect to topography and drainage.

PHYSIOGRAPHY

West Columbia salt dome has for its surface expression a faint horseshoe-like rim rising from 5 to 12 feet above the surrounding prairie (Fig. 2). The central basin opens toward the northeast into Varner Creek, a tributary of Brazos River. Erosion by the creek has removed most of the rim on the northeast. The floor of the central basin is 5–10 feet below

[1] A more detailed history of West Columbia can be found in the paper by D. C. Barton, *op. cit.*, pp. 213–15.

the level of the prairie. In dry weather there is a marsh in the basin separated from Varner Creek by a remnant of the rim or a natural levee of the creek.

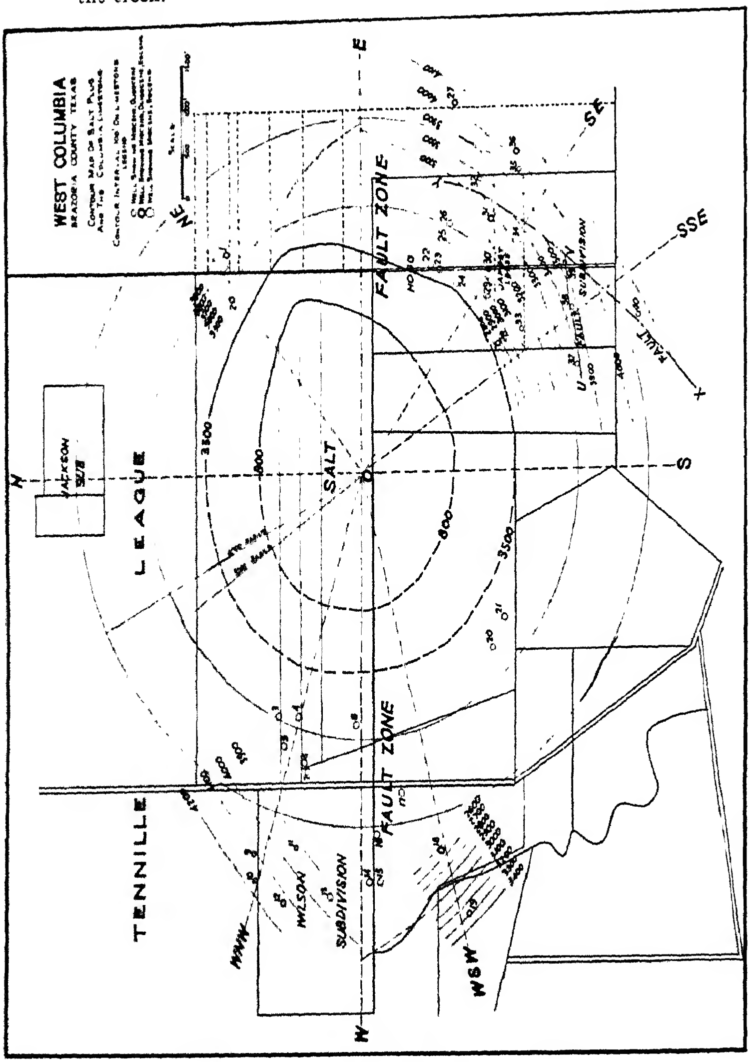

FIG. 3.—Subsurface structure of West Columbia contoured on salt plug and Columbia limestone. Contour interval on limestone, 100 feet. Scale of map in feet.

SURFACE GEOLOGY

The beds exposed in the vicinity of West Columbia field are the clays and sandy clays of the Beaumont formation, Pleistocene in age. The

mound appears to have a more sandy soil than that of the surrounding territory.

SUBSURFACE GEOLOGY

A contour map showing the subsurface structure of the West Columbia salt dome is shown in Figure 3, and further details of subsurface conditions are shown in sections and drawings of the dome in Figures 4–8, inclusive.

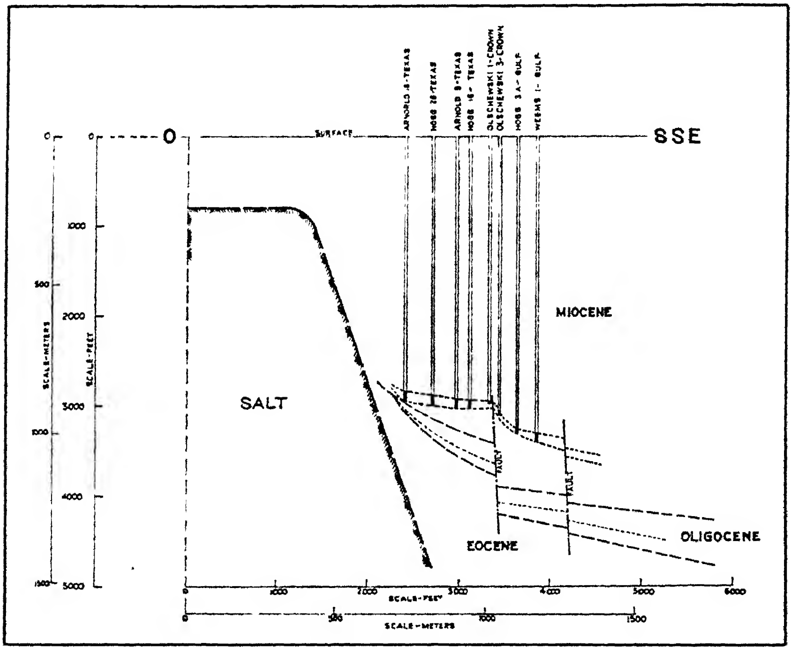

FIG. 4.—Section *SSE*, West Columbia (see Fig. 3).

The dome at West Columbia has a salt core, a truncated cone in shape, with a relatively flat top, standing at an average elevation of 800 feet below sea-level. The plan of the salt core is nearly circular, the 800-foot and 3,500-foot contours nearly concentric, and respectively 3,000 feet and 4,500 feet in diameter. The slope of the sides of the salt core is determined by a 2,700-foot drop in 750 feet horizontal distance, or a 4-to-1 slope. The shallowest salt is found at 768 feet below sea-level, and the deepest well to reach salt found it at 4,216 feet. The best data on the salt are found in wells on the northeast and east flanks of the stock. The position of the salt is largely determined by the negative control of deep

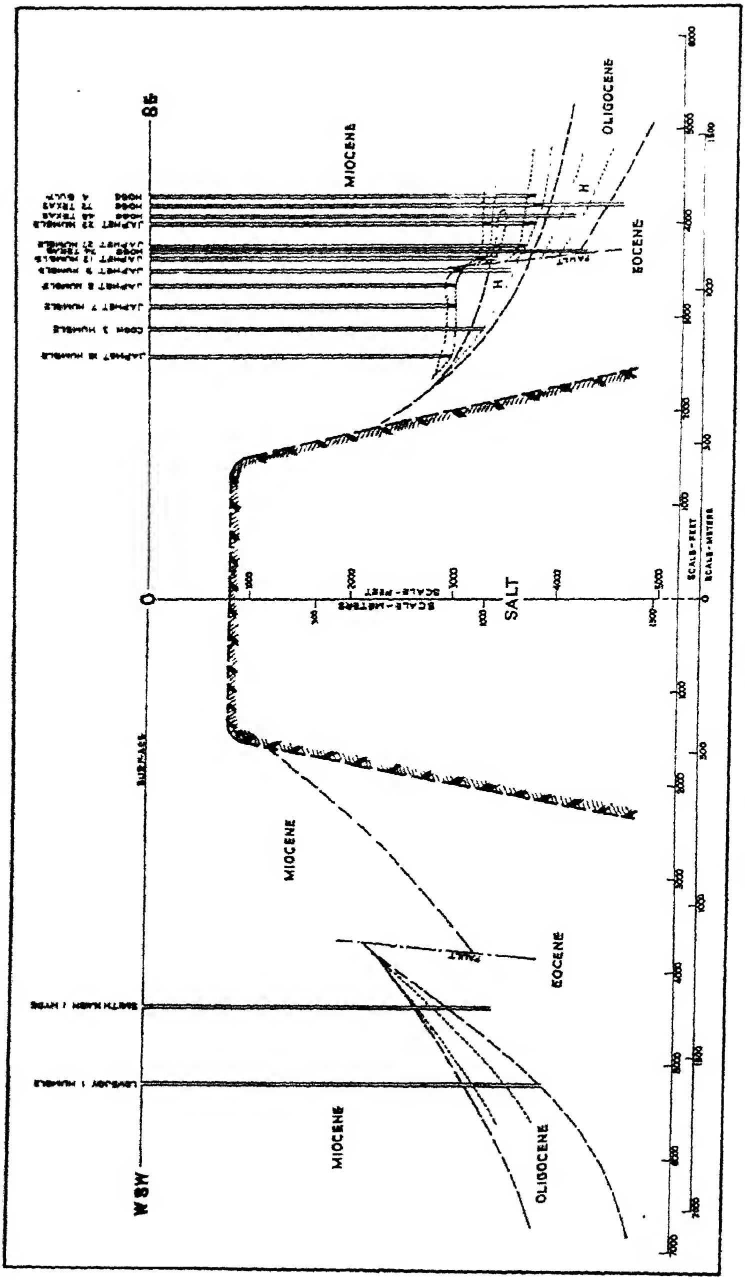

FIG. 5.—Sections *SE* and *WSW*, West Columbia (see Fig. 3).

wells which were drilled "off side" the core, and delimited the salt, although it was not actually encountered.

CAP

The cap rock at West Columbia consists of anhydrite and gypsum. It partly covers the salt, ranging from 100 to 150 feet in thickness on the north edge, probably pinching out toward the south.

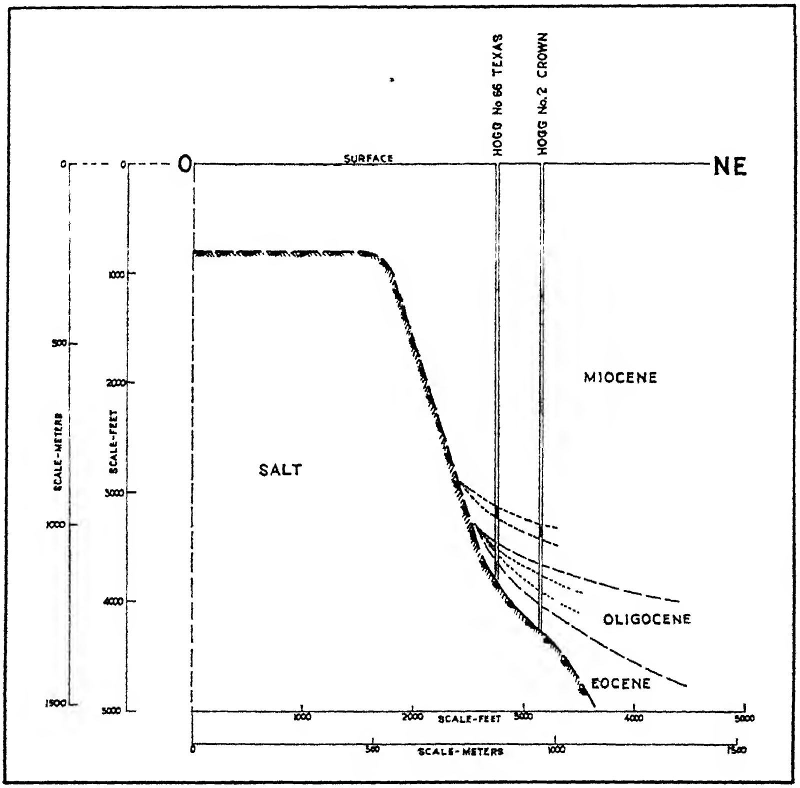

FIG. 6.—Section *NE*, West Columbia (see Fig. 3).

SUPER-CAP SEDIMENTS

The slight doming of the surface at West Columbia is evidence of the uplift of beds above the cap rock in Pleistocene time. The basin in the top of the mound is probably the result of removal, by solution, of some of the supporting salt at the top of the core which allowed the sediments on top of the dome to slump. Scarcity of wells on the cap, and lack

of cores or samples, have prevented a detailed study of these beds. The wells drilled to the cap or salt began in the sandy clays of the Beaumont, and there is no record of older formations above the dome. These super-cap sediments at West Columbia have not produced oil wells of commercial importance.

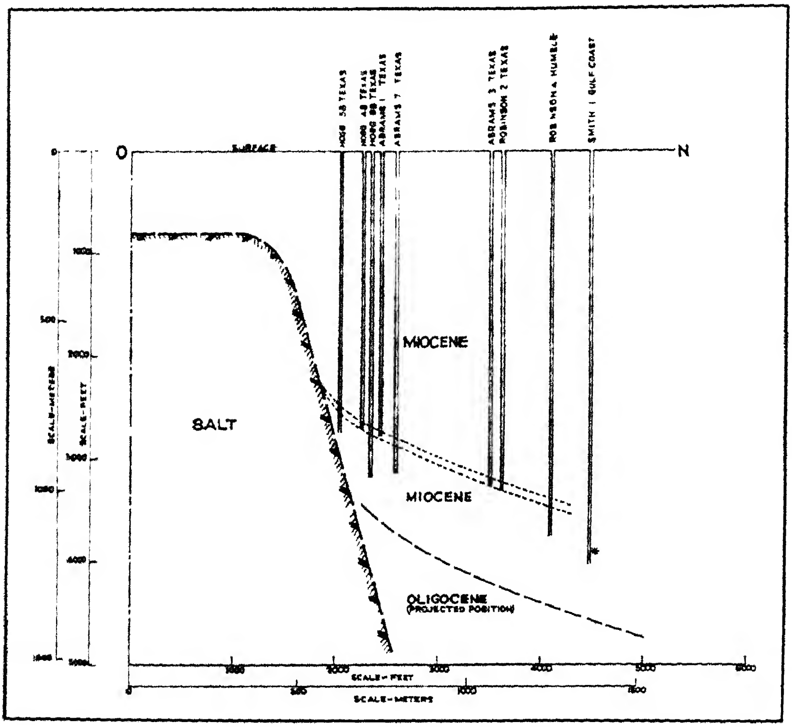

FIG. 7.—Section *N*, West Columbia (see Fig. 3).

SURROUNDING SEDIMENTS

The salt core at West Columbia is known to penetrate Eocene, Oligocene, and the lower three-fourths of the local Miocene-Pliocene-Pleistocene series. After a thorough lithologic and paleontologic study of the samples in Lovejoy No. 1 drilled by the Humble Oil and Refining Company on the southwest side of the dome, the section in this well is presented as a geologic section for West Columbia (Table I).

For purposes of this report the Miocene-Pliocene-Pleistocene series is called "Miocene"; the coral limestone of the *Heterostegina*-bearing zone

of the Oligocene, which has been described by Miss Ellisor[1] is, for simplicity, referred to as the "Columbia lime."

In the study of the subsurface of West Columbia, logs of all wells were collected, the sample files of the companies operating the field were searched, and all available cores and cuttings were thoroughly examined. No attempt was made to differentiate the Miocene. The Middle Oligocene was recognized as having three zones, the *Discorbis*, the *Heterostegina*, and *Marginulina*, so named from the characteristic fossil in each

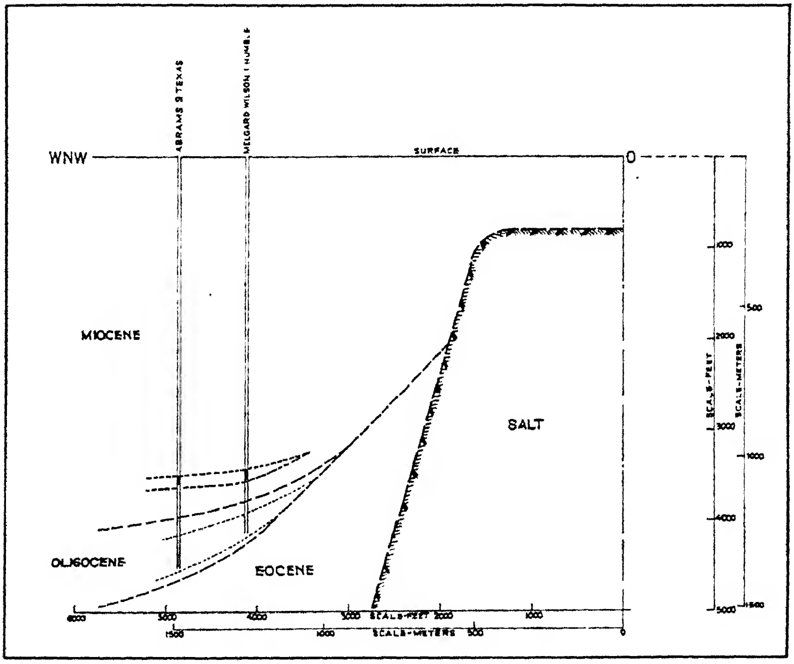

FIG. 8.—Section *WNW*, West Columbia (see Fig. 3).

zone. In the *Heterostegina* zone, the Columbia lime was selected as a key bed upon which contours might be drawn because it was hard, easily recognized in drilling, and found on all flanks of the dome. The Eocene was recognized by its foraminiferal association or, in drillers' logs, by the term "heaving shale." Drillers easily recognize the "heaving shales." Sample determinations fix the age of these shales as Eocene.

Figure 3 is a subsurface map of West Columbia. The salt plug is in-

[1] A. C. Ellisor, "Coral Reefs in the Oligocene of Texas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 976–85.

dicated, and contours are drawn on the Columbia lime as determined by the data available and giving due consideration to the penetration phenomena of the dome. For convenience in discussion, the dome is divided into four quadrants, the first being the northeast, and the others numbered counter-clockwise as in trigonometry. All cross sections are designated by the direction taken from the center of the salt core.

TABLE I

GEOLOGIC SECTION OF WEST COLUMBIA HUMBLE OIL AND REFINING COMPANY'S LOVEJOY NO. 1

Series	Formation or Type Fossil	Depth in Feet	Remarks
Pleistocene	Beaumont	Surface to 3,190	Varicolored sticky gumbos, sandy clays, clayey sands, and sandstones of non-marine and shallow-water marine origin characterized by re-worked Cretaceous *Foraminifera*, shallow-water forms such as *Rotalia beccarii*, *Polystomella*, *Striatapunctata*, ostracods, oysters
Pliocene	Lafayette		
Miocene	Fleming		
Oligocene (Middle)	*Discorbis*	3,190–3,295	Light gray and light greenish-gray shaly clays. No gumbo
	Heterostegina	3,295–3,576	Light gray fossiliferous limestone with few shale breaks
	Marginulina	3,576–3,870	Light greenish-gray calcareous sandy clay
Eocene (Jackson)	*Textularia hockleyensis*	Absent	
	Textularia dibollensis	3,870–4,405	Dark brown shaly clay, non-calcareous or slightly calcareous
	Bulimina	4,405–4,503	Dark brown calcareous unctious clay in places

DISCUSSION OF THE DOME BY QUADRANTS

FOURTH QUADRANT

In the fourth quadrant section *SSE* (Fig. 4) and *SE* (Fig. 5), together with the contour map, give a picture of the dome and adjacent sediments throughout a relatively large area. There is a gradual increase in tilt of the sediments as they approach the dome, and the older formations are tilted the most. The faults *UV* and *XY* (Fig. 3) are substantiated by logs

and paleontologic data. Wells No. 28, No. 31, No. 34, No. 37, and No. 39[1] establish the position of the upper block of Columbia lime, and Wells No. 22, No. 32, No. 35, No. 36, No. 38, and No. 40 establish the lower block. The displacement in the Columbia lime, along the fault, is approximately 400 feet.

On the upper block of Columbia lime the Miocene rests directly on the limestone, the *Discorbis* zone of the Oligocene having been eroded or pinched out. Over the lower block of Columbia lime the Miocene rests directly on the *Discorbis* zone of the Oligocene.

The faults *UV* and *XY* are reflected in the Miocene producing sands directly above the faults in the Oligocene lime, although the displacement is only 200 feet, about half as much as that in the lime. This condition indicates that part of the movement took place before the Miocene sands were deposited, and part after the deposition.

Section *SE* (Fig. 5) shows one sand over the upper block and three over the lower. The upper sand, which is found on both sides of the fault separating the two blocks, and the deepest sand over the lower block have proved to be the most reliable and were very prolific. Several very large wells were completed in the middle sand. These probably were fault-zone wells as they were found only on, and in the immediate vicinity of, the east end of the Japhet lease of the Humble Oil and Refining Company.

Just north of and approximately along the north line of the Japhet lease, production in the Miocene sands is very erratic. The Oligocene section is missing on the McMeans lease (Wells No. 25 and No. 26) and on the Bashara lease (Wells No. 22, No. 23, and No. 24), the drill passing from Miocene into the "heaving shale" of the Eocene. The Miocene producing sands, in this area of erratic producing wells, are deeper northward from the north line of the Japhet lease than those an equal distance from the center of the salt core and above the Columbia lime on the south. The great productivity of the wells over this Columbia lime may be attributed to the fact that the Miocene sands above the lime were carried upward with it in a relatively undisturbed condition. The sands were of excellent character and in position to become oil reservoirs, sealed on the northwest by the dome movement zone and on the north by the disturbed zone in which the Miocene is slumped down on the Eocene.

Two or three of the wells on the Japhet lease on the upper block of Columbia lime obtained erratic production in the Oligocene. This was probably accidental and occurred because the Oligocene was here thrust

[1] These figures refer to the numbers given to the wells shown on the contour map of the Columbia limestone.

up in position to become a reservoir and was filled with oil just as the Miocene reservoirs were filled. No other Oligocene producing wells are known on this dome.

FIRST QUADRANT

The Columbia lime is found in two wells in this quadrant (Wells No. 1 and No. 2). Section *NE* (Fig. 6) and the contour map show the sediments adjacent to the dome in a very limited area. The Miocene sands are tilted more steeply than those in the fourth quadrant. The Oligocene section in Well No. 2 nearest the dome is 105 feet thick, the Eocene section 250 feet thick, and the salt was reached at 3,852 feet.

Section *N* (Fig. 7), extending from The Texas Company's Hogg No. 58 north across the Jackson subdivision, shows a Miocene sand with considerable tilting. Data in this quadrant are not sufficient to prove faulting in the vicinity of this section; however, when Hogg No. 68 and Abrams No. 7 of The Texas Company were projected onto section *N* by paralleling the salt contours, it was noticed that the producing horizon in these wells was 300 feet lower than the sand in the wells adjacent to the section line. Wells projected in the same manner from the west onto the section have the same producing horizon as those adjacent to the section. There is, therefore, a suggestion of a radial fault passing northeast somewhere between Texas Abrams No. 1 and No. 7. No wells on the north side of the dome have encountered Oligocene or Eocene formations.

SECOND QUADRANT

In this quadrant the position of the Columbia lime is determined by four wells, No. 9, No. 10, No. 11, and No. 12. Section *WNW* (Fig. 8), with the contour map, show the general subsurface conditions in a part of this quadrant. The Miocene and Oligocene beds are tilted more gently than in the first and fourth quadrants. Attention is called to the fact that this block of lime is much farther from the center of the salt core than the blocks in the two preceding quadrants. The Oligocene gradually pinches out toward the dome and toward the south, and the wells pass directly from Miocene into Eocene. The Oligocene was found in Well No. 10 at 3,960 feet and was still in Columbia lime at 4,533 feet; Well No. 12 encountered it at 4,110 feet and drilled through it at 4,400 feet into Eocene; Well No. 13 drilled directly from Miocene into Eocene between 4,080 and 4,120 feet. In the southern part of this quadrant it should be noticed that many wells passed directly from the Miocene into the Eocene with the entire section of Oligocene removed by pinching, faulting, or erosion, or a combination of all the processes.

THIRD QUADRANT

The contours on Figure 3 and section *WSW* (Fig. 5) are used to show subsurface conditions in this quadrant. Unfortunately data are sufficient to show only the dip in the Columbia lime (Wells No. 18 and No. 19). Especial attention is called to the distance of this block from the center of the salt core, and its elevation as compared with the blocks in other quadrants. Wells No. 15, No. 16, No. 17, No. 20, and No. 21 drilled directly from Miocene into Eocene. Well No. 18 encountered Oligocene at 2,680 feet, passed out of it at 2,926 feet into Eocene, and continued drilling in it to a total depth of more than 3,400 feet. Well No. 19 (Lovejoy No. 1 of the Humble Oil and Refining Company) encountered Oligocene at 3,190 feet, drilled out of it at 3,870 feet into Eocene, and was abandoned in Eocene at 4,623 feet. There were no reliable data obtainable on the south side of this dome, though, judged from lithology in the well logs, the formations penetrated were probably Miocene.

DOME-PENETRATION PHENOMENA AT WEST COLUMBIA

The salt dome at West Columbia began its upward movement through an east-west fault or line of weakness. The stock split open the fault just as a pencil point splits open a slit in a piece of paper when thrust through the cut. The points of greatest pressure on the salt were on the north and south sides, and the areas of least pressure on the east and west sides. Into the areas of low pressure and gaps in the Columbia lime, the Eocene was pressed upward and the Miocene collapsed downward to come into contact with the Eocene. In addition to the primary fault through which the dome began its movement, there were developed several radial and peripheral faults, some clearly decipherable and others suggested; but because of meager data, these were not definitely proved.

Figure 3 shows that the plans of the blocks in the second and fourth quadrants are fixed by three or more wells in each block. In the first and third, with only two wells to the block, only the dip is definitely fixed. Because of the attitude of the blocks in the second and fourth quadrants, it seems reasonable that the blocks in the first and third should occupy a similar attitude with respect to the salt stock, and these were therefore drawn as shown on the map.

There is considerable difference in elevation of the lime in the four quadrants. The two blocks on the north side of the original fault are lower than the two on the south. The two blocks of lime west of the center line of the dome are much farther from the center of the salt mass than the two on the east. Since the lime in the first and fourth quadrants is

much closer to the dome, it is reasonable to believe that the east side of the salt mass is very steep. The much greater distance of the lime blocks on the west, from the center of the salt, suggests a more gentle slope of the salt, although the meager data available do not prove it. The fact that the lime blocks are much higher in the two southern quadrants suggests that there must have been some projection or obstruction on the upward-moving salt mass, which carried parts of the blocks to higher elevations than the blocks on the north side of the primary fault.

At a distance of 4,500 feet from the center of the salt, the elevation of the Columbia lime as determined by wells, or projection of the known dip of the lime, is as follows:

First quadrant,	−5,000 feet	(projection)
Second quadrant,	−4,100 "	(wells)
Third quadrant,	−2,800 "	(wells)
Fourth quadrant,	−4,100 "	(wells) (lower block)
	−3,900 "	(projected) (upper block)

The greatest differential uplift in the lime is 2,200 feet between the first and third quadrants; and the least, zero feet, between the lower block in the fourth quadrant and the segment in the second quadrant.

In order to throw further light on structural conditions surrounding this dome, the three truncated sections of Figure 9 were drawn. The truncations were made at elevations of −3,000, −3,400, and −3,900 feet by means of the contour map on the Oligocene and the sections shown in Figures 4–8. The −3,000-foot section shows the salt core with the Oligocene appearing on the south side of the dome; the section −3,400, the Oligocene in the first, third, and fourth quadrants; and the section −3,900, the Oligocene in all four quadrants of the dome, practically surrounding the dome.

For a more thorough understanding of the subsurface at West Columbia a perspective drawing of the dome was constructed, using the contour map in Figure 3 as a basis for the picture which is shown in Figure 10. The viewpoint of the observer is at a point 500 feet above the surface of the ground east of the dome, and the observer looks from this point due west over the center of the salt mass. The rim and surface basin are shown. By removing all the Miocene sediments from a part of the cap, salt, Oligocene lime, and Eocene, one is able to see the attitude of the sediments older than the Miocene with respect to the salt core, and also to see in the "wall" sections the attitude of the Miocene beds with respect to the Oligocene and the salt. The drawing had to be augmented in some detail in order to make a complete picture, but nothing was added

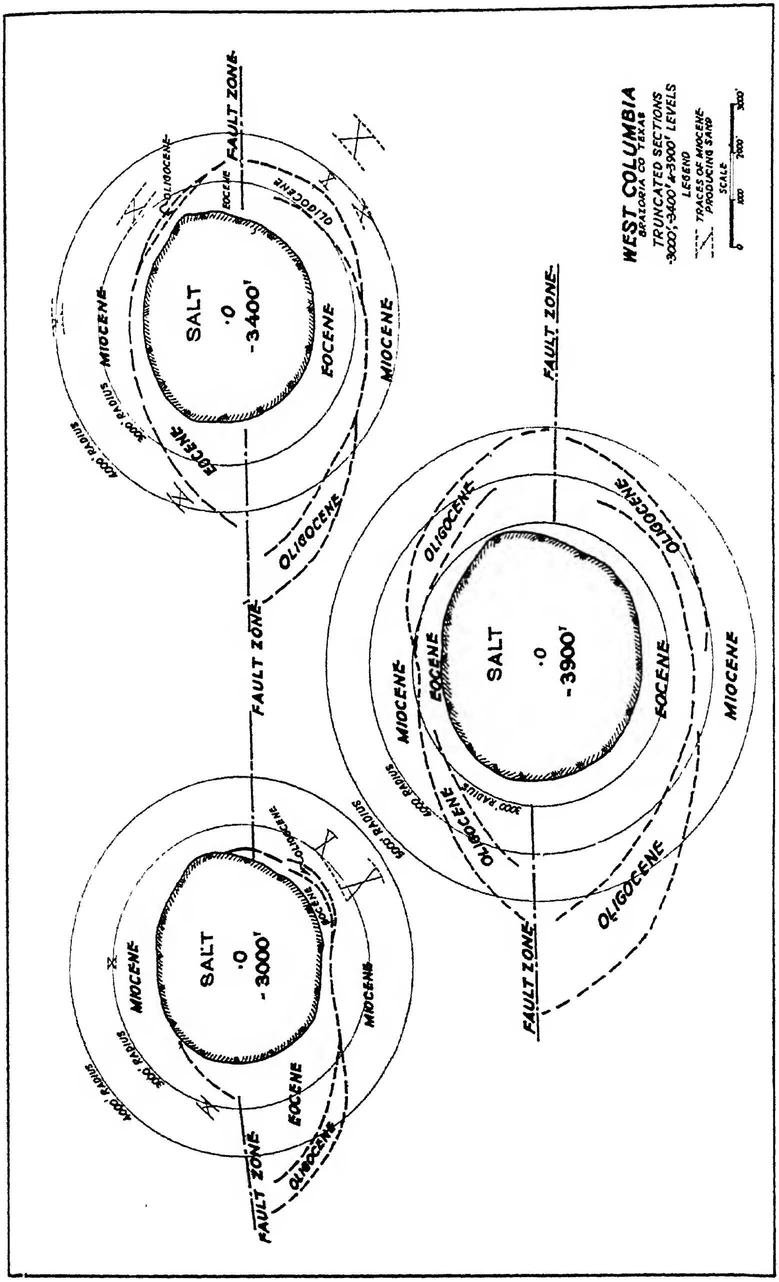

FIG. 9.—Truncated sections of West Columbia salt dome at 3,000, 3,400, and 3,900 feet below sea-level. Scale in feet.

which does not correspond with the general condition of the salt and its surrounding sediments. The faults in the Columbia lime and the area of Eocene in the rift between the two major Oligocene segments upon which Miocene sediments rested, are shown. The Miocene producing sands shown on the left wall of the cut have been transposed to that position from a position nearer the Eocene area. The Miocene producing sands

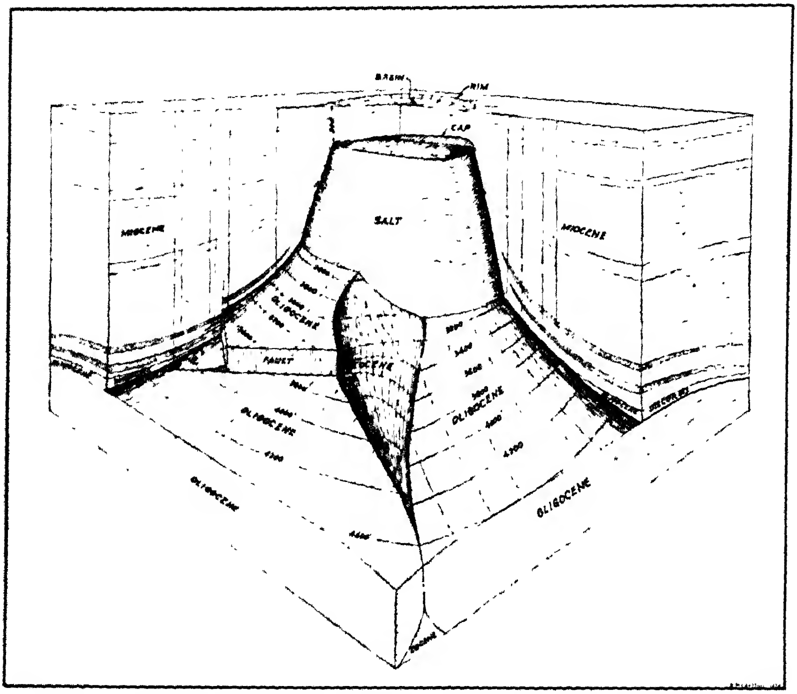

FIG. 10.—Perspective drawing of West Columbia salt dome. Depths in feet.

on the right wall of the cut show the general attitude of the producing sands on the north side of the dome. This perspective drawing was made to show the major features of the dome. It is undoubtedly too smooth and too regular, and no doubt there are other minor faults and irregularities. Too much detail would complicate the picture.

RELATION OF THE ACCUMULATION OF OIL TO STRUCTURE

At West Columbia the production is found in the lateral sands of Miocene age. In those exceedingly prolific sands in the fourth quadrant,

production comes from sands which were carried upward on the Oligocene lime with little disturbance except for the fault which divided the blocks. The nearly vertical fault zone between these blocks produced several very large wells. The Miocene sands in the Eocene area north of the Japhet lease yielded fair production, but the position of the sands is very erratic, owing to slumping.

In the Miocene sands associated with the blocks of Oligocene lime in the first and fourth quadrants has been found some excellent production. The remarkable production obtained by The Texas Company on the Abrams and Hogg leases on the north side of the dome comes from Miocene sands whose relation to the Oligocene is not known. These sands are rather steeply tilted though very regular, and probably were carried up intact on the Oligocene during the movements of the salt core.

Salt stocks in moving upward produce doming of the sediments around and above the cores. If petroleum source beds have been uplifted or penetrated, there should be an oil accumulation, provided there are reservoirs in either the super-cap sands, the cap rock, or the lateral sands. It should be expected that if a dome merely uplifts the sands in which the oil is indigenous, the only production would be obtained from super-cap sands. If the salt core penetrates the source beds, it is to be expected that the lateral sand reservoirs would be filled first, and that, given some avenue of escape, the oil would move upward into either porous cap, or super-cap sands, or both, depending on conditions on the dome. The Spindletop dome in Jefferson County, Texas, has all three types of reservoirs known to the coastal domes of Texas and Louisiana, namely, super-cap sands, cap rock, and lateral sands. West Columbia has only one type, lateral sands.

PRODUCTION

The production of the West Columbia field by years is shown in Table II. The productive area of the field is approximately 330 acres, and the production per acre approximately 200,000 barrels. The 20 acres of the Japhet lease held by the Humble Oil and Refining Company has produced 12,415,806 barrels of oil—620,298 barrels per acre. The curve in Figure 11 shows the decline and cumulative curves for the whole West Columbia field and the Japhet lease. The Texas Company's Hogg No. 80 was completed on September 3, 1924, making 12,000 barrels of oil a day from a depth of 2,775 feet; and by July 8, 1928, had produced 2,700,000 barrels of oil. It is now producing approximately 1,300 barrels daily. The Texas Company's Abrams No. 1, completed July 20, 1920, to date has produced more than 3,000,000 barrels of oil and is now pumping at the

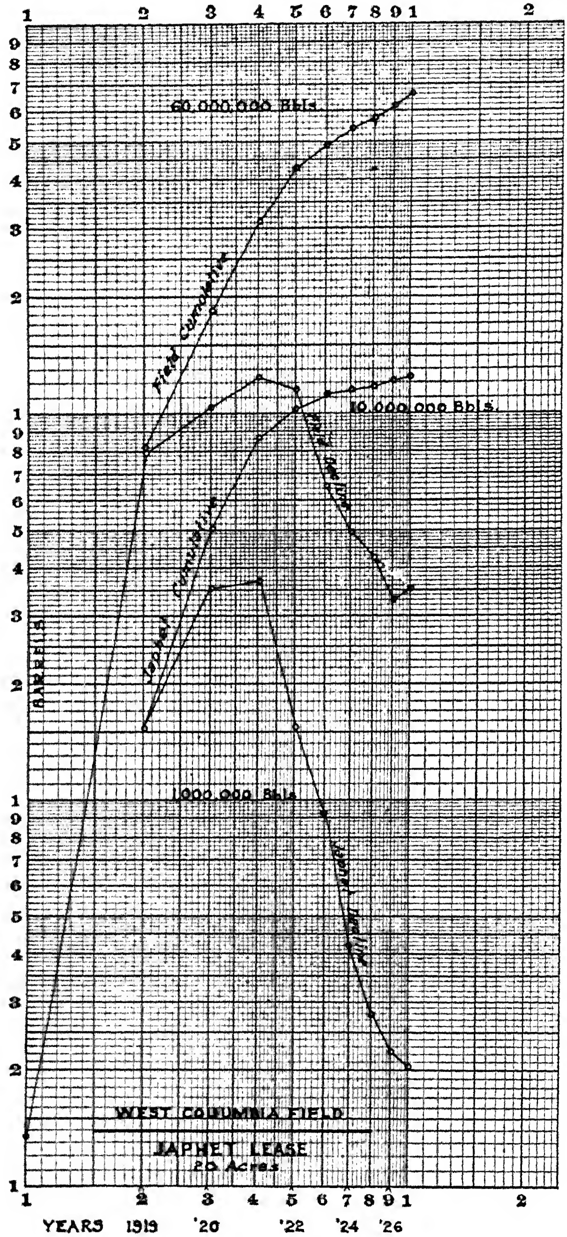

FIG. 11.—Production curves of West Columbia oil field and Japhet lease.

rate of 100 barrels daily. The Texas Company's Hogg No. 58 was completed on May 18, 1921, and has produced slightly in excess of 3,100,000

TABLE II

PRODUCTION, WEST COLUMBIA FIELD

Year	Barrels
1918	136,000
1919	8,129,000
1920	10,563,000
1921	12,573,000
1922	11,632,000
1923	6,599,000
1924	4,964,000
1925	4,230,000
1926	3,330,000
1927	3,535,000
1928[1]	2,946,000
Total	68,637,000

barrels to date and is now producing at the rate of 800 barrels per day. This well has never made any sediment or water.

[1] 1928 figures were added after report was written.

RELATION OF ACCUMULATION OF PETROLEUM TO STRUCTURE IN STEPHENS COUNTY, TEXAS[1]

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ABSTRACT

Stephens County, in north-central Texas, is situated on the axis of the Bend arch, one of the most important buried structural features in Texas. The most widespread occurrence of oil in the Bend series, of basal Pennsylvanian age, has been found in this county. Oil is also produced from sands in the Strawn formation, above the Bend. The control of oil accumulation is essentially anticlinal.

INTRODUCTION

Stephens County is in north-central Texas, approximately 90 miles south of Red River and the same distance west of Fort Worth.

It is drained by the tributaries of Brazos River. These tributaries are intermittent streams flowing northward into the river which flows in a general direction toward the east and north, gradually swinging southeast and eventually reaching the Gulf of Mexico.

Geologically,[3] the county is in the Pennsylvanian area of north-central Texas. The Upper Pennsylvanian sediments constituting the surface rocks dip beneath the Permian on the west and are covered by Cretaceous on the east. The pre-Mississippian rocks of the Llano-Burnet uplift form the southern boundary of the Pennsylvanian beds.

PRODUCTION

The first well was brought in during the latter part of 1916. By December, 1920, the county reached its peak of production. During that month the daily average production per well was 122 barrels from 893

[1] Manuscript received by the editor, November 10, 1928.

[2] Humble Oil and Refining Company.

[3] Among previous papers describing this area are the following: Clarence S. Ross, "The Lacasa Area, Ranger District, North-Central Texas," *U. S. Geol. Survey Bull. 726-G* (1921); H. H. Adams, "Geological Structure of Eastland and Stephens Counties, Texas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 4, No. 2 (1920); and Wallace E. Pratt, "Geologic Structure and Producing Areas in North Texas Petroleum Fields," *ibid.*, Vol. 3 (1919).

wells. The total daily production was 109,917 barrels. At present the rate of production of 1,197 wells, total, had declined to 6,800 barrels per day.

The county has produced 113,777,926 barrels, total, since the discovery well. The production has come from wells throughout the entire county, but almost half of the total has been produced in and near the county seat, Breckenridge, in an area of approximately 15 square miles. In this area, the average leases have produced 5,000 barrels per acre, with the wells which are still producing averaging 6 barrels per day.

STRATIGRAPHY

The Pennsylvanian sediments are divided into the upper and lower Pennsylvanian, separated by an angular unconformity. The upper Pennsylvanian has been divided into three groups, the Cisco, Canyon, and Strawn, the surface rocks in the county being in the two upper groups.

The Strawn consists of coarse sandstones, blue shales, and sandy shales, and is approximately 2,000 feet in average thickness in the southeastern part of the county, where it is oil-bearing. Of the total production of the county, it is estimated that approximately 5,000,000 barrels have been produced from this group, the remainder from the lower Pennsylvanian, or Bend. The comparatively small amount of production from the Strawn is found at depths ranging from 1,350 to 2,400 feet.

The lower Pennsylvanian, together with the underlying Barnett shale, which is questionable in age, is known as the Bend series and consists of black shales and heavy massive-bedded black and gray limestones. The Bend series is separated from the underlying rocks by an erosional and possibly angular unconformity. The lower Pennsylvanian is divided into the Smithwick and Marble Falls formations, with a total average thickness in the county of 1,100 feet. The principal producing horizon in the Bend is the Caddo, or Breckenridge, limestone, a lenticular lime in the Smithwick shale, which is variable in its character throughout a broad area.

In places it is a well-developed, massive, hard limestone which must be broken by heavy charges of nitroglycerin before it yields oil. In other areas it is a porous, sandy lime which produces freely upon being penetrated. In still other areas it is practically missing in the section, its place being taken by thin lime shells or black shale.

STRUCTURE

The upper Pennsylvanian beds which form the surface rocks of the county have a regional dip toward the west or slightly north of west at a

rate ranging from 40 to 60 feet to the mile. This general monoclinal structure is interrupted by plunging anticlinal dip folds and by terraces. The dip folds may extend for miles, the rate of dip along the axes ranging from 100 feet to the mile to no dip. Here and there are small domes on the axes of the folds, with closures ordinarily less than 10 feet. The terraces may extend along the strike for some distance, with small plunging noses projecting across the flattening in the beds. The axes of the well-known dip folds and the strike of the terraces are shown on the accompanying subsurface map (Fig. 1).

SUBSURFACE STRUCTURE

Strawn.—Owing to the character of the Strawn deposits, it is not practicable to map the subsurface on any one horizon and endeavor to cover any appreciable area. The sands are not blanket sands, and no extensive limestones were deposited. The small pools produce from different horizons.

Subsurface maps of these pools, based on the producing sand of each, show in some pools small domes with a closure ranging from 10 to 50 feet, which may cover an area of ½ square mile. In other pools, production is obtained on plunging anticlines with different amounts of closure, and with abnormal dips on the flanks ranging from 20 to 100 feet per mile. In still other pools a dip fold very similar to common surface folds is mapped.

Bend.—The folding in the lower Pennsylvanian beds is shown in Figure 1. The contours of this map are based on the top of the Caddo limestone or, in areas where the Caddo is not well developed or is missing, upon the top of the Marble Falls limestone, which is the top member of the Marble Falls formation in the Bend group and is at an average interval of 300 feet below the position of the Caddo. The contour interval is 100 feet, and minor structural features are not portrayed.

The log sections (Figs. 2 and 3) give a picture of the regional attitude of the upper and lower Pennsylvanian beds.

The county is located on the axis of a northward-plunging geanticline named the Bend arch. No particular line can be drawn representing the axis of the structure, although in a broad sense it might be described as extending from the outcrop of the Bend sediments in San Saba and McCulloch counties, through the west part of Brown County, swinging northeast and passing near Ranger, in Eastland County, swinging back toward the north, and passing through the area west of Ivan, Stephens County.

The arch, as pictured, is very similar in magnitude and major struc-

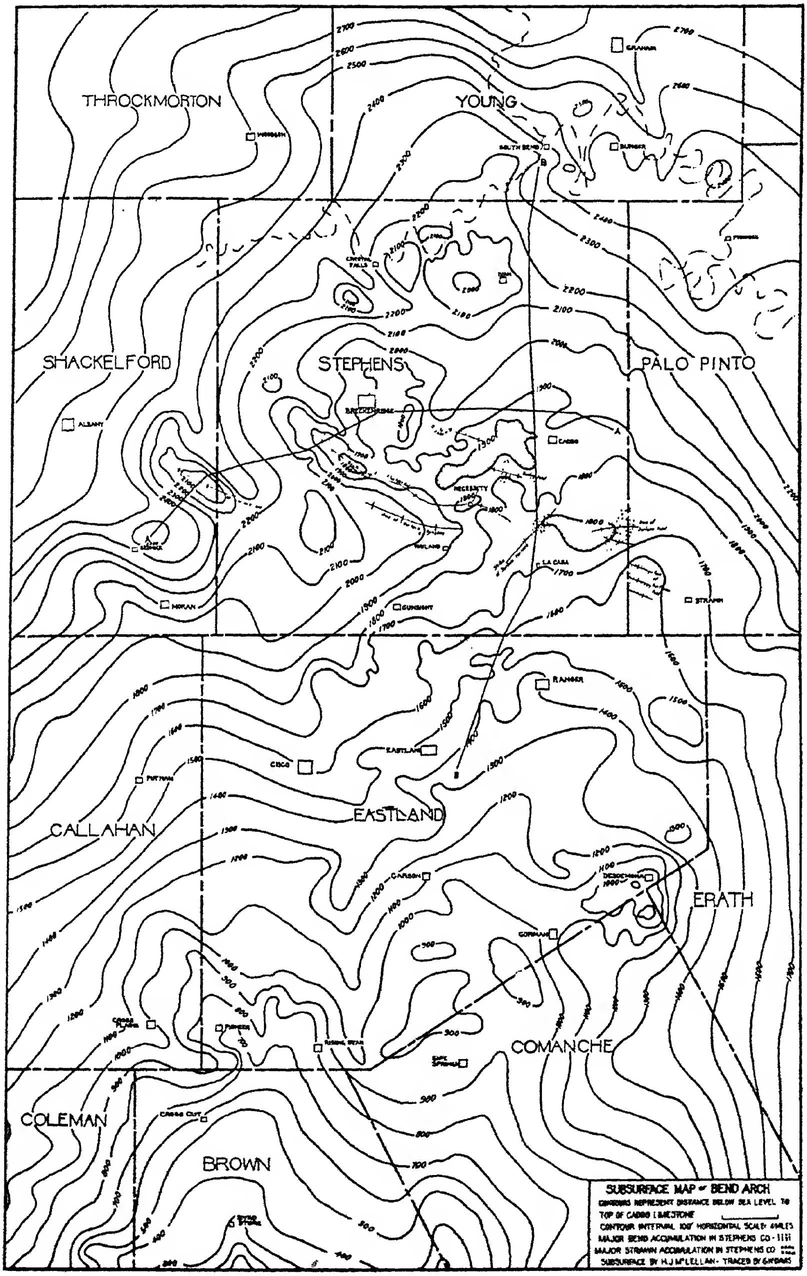

FIG. 1.—Subsurface structure of Bend arch, Stephens County, Texas, contoured on top of Caddo limestone below sea-level. Contour interval, 100 feet.

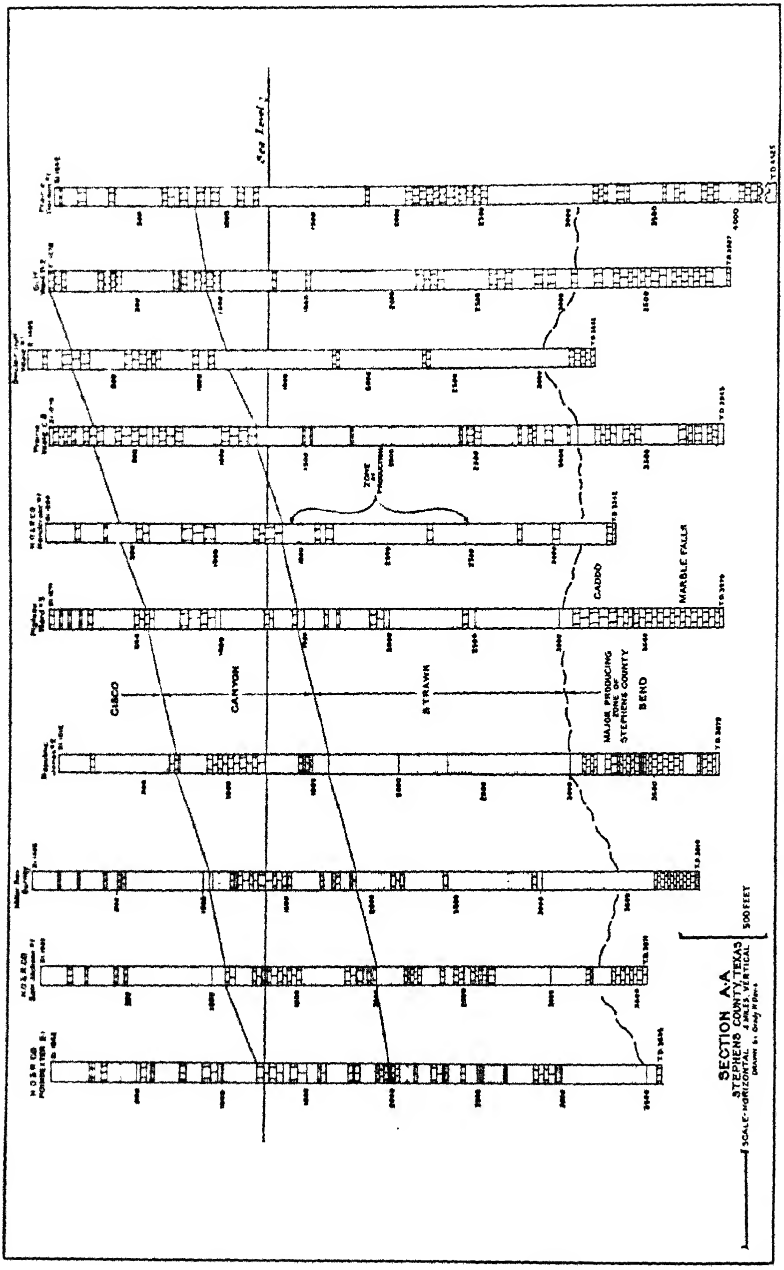

FIG. 2.—Section *A–A* (Fig. 1), Stephens County, Texas.

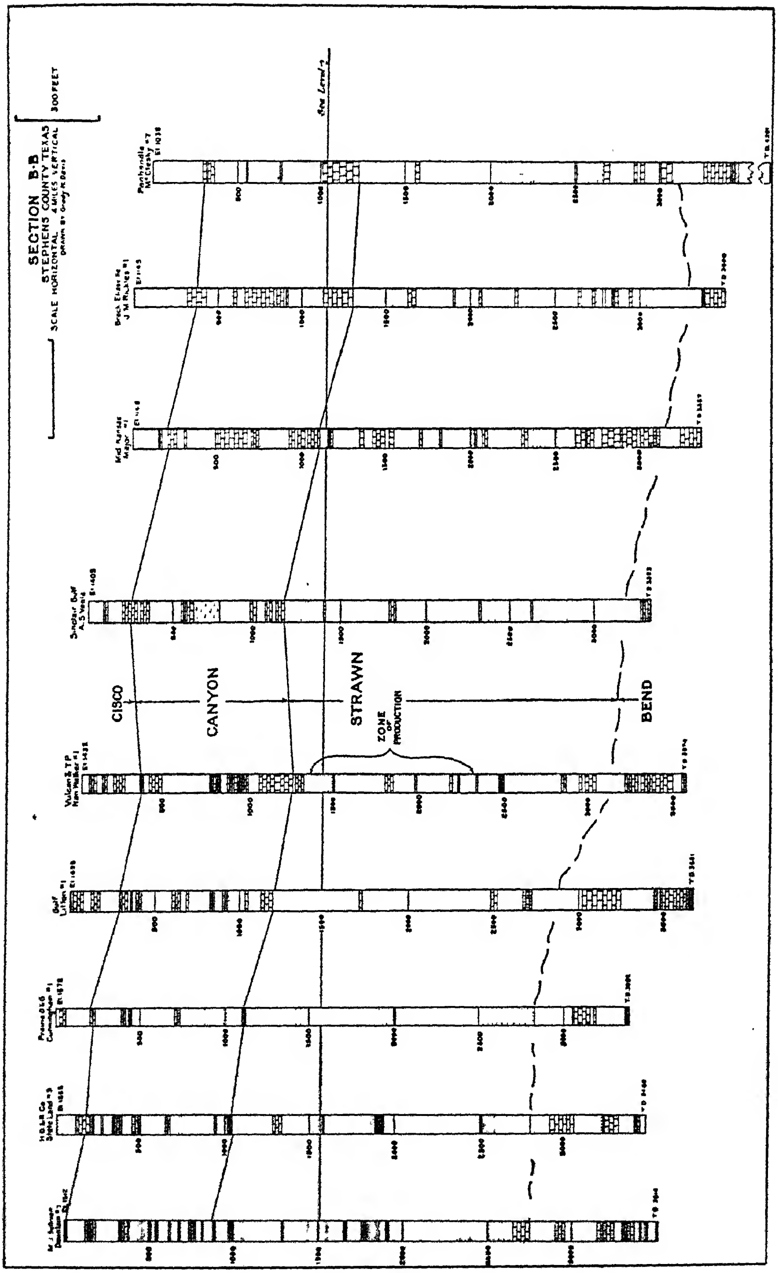

FIG. 3.—Section *B–B* (Fig. 1), Stephens County, Texas.

tural features to a subsurface map published by M. G. Cheney in the *Oil and Gas Journal*, April 12, 1928, which is based on the pre-Mississippian surface on which the Bend was deposited unconformably.

COMPARISON OF SURFACE WITH SUBSURFACE STRUCTURE

Strawn.—The folding throughout the upper Pennsylvanian is closely reflected by the surface beds. However, owing possibly to a slight discordance between the Canyon and the underlying Strawn, or to pre-Canyon movements, the folding is more severe in the Strawn than shown by surface mapping on the Canyon and Cisco beds. Underlying a terrace in the surface beds, there may be a series of small plunging dip folds, or closed structures in the Strawn, extending along the strike of the terrace, with the areas of least dip along the axes of the folds occurring directly beneath the surface terrace. Underlying the area of least dip along the axis of a dip fold in the surface beds, the Strawn sands may show the presence of a dome, or a plunging anticline, with reversals ranging from 10 to 50 feet.

Bend.—The surface beds do not reflect the regional subsurface structure of the Bend. The major surface folds, however, are reflections of minor movements in the Bend. Almost every subsurface dome or plunging anticline on the Bend arch is found under surface terraces or dip folds. All surface terraces or dip folds, however, do not overlie folds in the Bend. Many surface domes or anticlines are directly over synclines in the lower Pennsylvanian. The closure or flattening in the Bend is ordinarily found down-dip from the flattening in the surface beds, the horizontal shift of the top of the structure ranging from ¼ mile to 2 miles, as in the Parks fold, whose axis extends through the Curry pool, southwest of Breckenridge. Folding in the lower Pennsylvanian sediments is a much greater magnitude than indicated by surface structure, domes and plunging anticlines with closures ranging from 50 to 200 feet being common in the Bend.

RELATION OF ACCUMULATION IN STRAWN TO SURFACE STRUCTURE

The present pools in the Strawn are all in the southeast part of the county, as shown in the subsurface map (Fig. 1). There is no marked difference in the type or magnitude of structures in that area as compared with the rest of the county. Neither is there any difference in average rate of dip. The accumulation in a regional sense, therefore, can not be related to surface structure. Accumulation occurred in the southeast part of the county simply because conditions were more favorable there.

Local accumulation, however, is definitely related to surface structure. The pools are situated on the axes or flanks of the surface dip folds or on the surface terraces. The northwest flank is the common area of accumulation, and in most pools the best production is obtained from that part of the structure. Theoretically, this is the structural position for accumulation to take place, where the regional dip is toward the northwest; and the theory is borne out by present production.

RELATION OF ACCUMULATION IN STRAWN TO SUBSURFACE STRUCTURE

As stated in a previous paragraph, subsurface structure in the Strawn is closely related to surface structure as mapped on the two upper groups in the upper Pennsylvanian, with the folding more pronounced in the Strawn than in the overlying beds. Accumulation with respect to subsurface structure, as shown by detailed subsurface maps based on the producing sands in the various pools, is on the top of small domes, or on either flank, or on the axes of the dip folds. The best production is found where, theoretically, it should be, either within the closed part of the structure or on the northwest flank. It should be stated, however, that what seems to be a fold could be partly due to change of thickness in the sand body; and, there being no definite marker except the producing sand, it is highly probable that part of this steepening and reversal of dip in the Strawn is not structural but merely variation in thickness of the sand bed. The factor of variation in thickness of the sand body from no sand to 100 feet is very important in the location of accumulation of oil. It is evident that the oil must seek a reservoir; and should the sand body necessary for this reservoir be thin or changed to sandy shale on the northwest flank or top of the structure, and thick on the south flank, accumulation will take place on the south flank. This is the condition in some locations, but nearly all production, where thus found, is unimportant.

RELATION OF ACCUMULATION IN BEND TO SURFACE STRUCTURE

As shown in a previous paragraph, structure in the Bend commonly shifts down-dip from surface structure, and accumulation is ordinarily found some distance down-dip from its theoretical location, as judged from surface folding.

RELATION OF ACCUMULATION IN BEND TO SUBSURFACE STRUCTURE

The great Bend arch presents a magnificent structure for the accumulation of petroleum. On the regional axis of this arch, up-dip, where the first major flattening and reversals occur, is Stephens County. In this

county, and slightly west of the axis of the arch, is a subsurface structure with almost 200 feet of closure, which covers an area of approximately 25 square miles. On this structure the greatest accumulation of oil and gas on the arch has been found. Although there is no definite water table in the county, nevertheless, in general, the water, oil, and gas occur according to their theoretical sequence on structure; and the Humble Oil and Refining Company's G. W. Keathley No. 1, probably the greatest gas well in the history of Stephens County, is on the highest part of the Breckenridge structure. The major accumulation of oil is found down-dip on the northwest, and water is encountered at approximately 1,900 feet below sea-level in the producing formation.

Petroleum is found in some local structural basins in the Bend, and in some instances accumulation has taken place so far down on the flanks of the plunging anticlinal folds that it appears to be almost synclinal. It is the writer's opinion that under such conditions the accumulation is still anticlinal in a broad sense because the local closed basins and the flanks of the anticlinal folds are all high structurally when viewed with respect to their position on the Bend arch. The rather negligible accumulation located in locally low areas on the general high is due to local modification in the characteristics of the producing zone, or to the presence of crevices which extend through the limestone and serve as conduits connecting an accumulation under pressure with the local structural low, or possibly to lack of pressure necessary to force the petroleum to local structural highs.

The relation of accumulation to structure in the Breckenridge pool is typical of the pools in the west two-thirds of the county. The Curry pool, southwest of the Breckenridge "high," is on a plunging anticlinal fold extending halfway across the county, with gas on the closures, and oil down-dip on the axis and flanks, and the major accumulation on the north flank. The production at Ivan, in the northern part of the county, is on the down-dip flank of a dome with a closure of approximately 150 feet, with gas on the top of the structure. In the northeastern part of the county, where the regional dip in the Bend is toward the northeast, the axes of the subsurface folds in the Bend extend in a general way southwest and northeast. In this area, the North Caddo and Hart pools are on the axes of plunging anticlinal dip folds, and the major accumulation of petroleum on the east flanks of the structures.

SUMMARY

Figure 1 shows the relation of accumulation to regional structure. The relation to local structure is also shown, although a detailed map

with smaller contour intervals would bring out the close relation more clearly.

In conclusion, it is the opinion of the writer that although sand conditions modify the theoretical structural location of accumulation in the Strawn, and the characteristics of the Bend limestone influence to some extent accumulation in the Bend, still it is impossible to doubt that accumulation of petroleum is definitely due to regional and local anticlinal structure; and, further, that the accepted theories of accumulation of gas, oil, and water on structure have been fully verified by development in Stephens County, Texas.

YATES FIELD, PECOS COUNTY, TEXAS[1]

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ABSTRACT

The Yates field, eastern Pecos County, Texas, is on the crest of a bifurcate domal fold developed in the Permian "Big lime." Subsurface folding in the Permian rocks is reflected by a similar anticlinal feature in the surface Comanche limestones. This dome, on the southwest margin of the Saline Basin geosyncline of West Texas, is a marginal fold on the general line of folding which extends through Upton and Crane counties. Production is from porous limestones near the top of the "Big lime." The prolific production of oil is, in large part, due to the high degree of porosity of the limestones under the influence of high hydrostatic pressure of the water immediately beneath the oil.

INTRODUCTION

The Yates field has now been sufficiently developed to demonstrate that it must be considered one of the major oil pools of the world. This oil field not only is great in the areal extent of the productive leases but is unique in prolific initial production from shallow depth.

The greater part of the proved area is held in large parcels by the major producers. Because of this fortunate lease ownership, development has for the most part been conservative, with a fair spirit of mutual co-operation prevailing to prorate the output and to prevent damage to the productive formations by unwise recovery methods. This co-operative spirit will, the writers believe, be reflected in an enormously increased recovery of oil per acre and in a prolonged life for this pool. Had these leases been held in small parcels by operators who had only personal interests, a mad scramble for the oil would have resulted, with, it is probably safe to say, one of the worst periods of overproduction ever experienced in the history of the oil industry.

The object of the writers is to present a résumé of the salient features of the geology and the conditions of accumulation of oil in this field. The data utilized in the preparation of this paper represent the work of the geological staff of The California Company. The mapping of the surface

[1] Manuscript received by the editor, November 26, 1928.

[2] Chief geologist, Standard Oil Company of California.

[3] Geologist, The California Company.

geology was done by The California Company geologists under the field supervision of Fred S. Wright. The descriptions of the stratigraphy as revealed from a study of the well cuttings are mainly the work of Lon D. Cartwright, Jr., and John Emery Adams. The interpretation of subsurface structure is, in large part, that of George L. Klingaman and Earle R. Wall. However, the writers wish to acknowledge their indebtedness to all those geologists and those operators who, by furnishing well logs and well samples, have contributed data for the paper.

HISTORY OF DISCOVERY

Oil was discovered in the Yates field by the Mid-Kansas Oil and Gas-Transcontinental Oil Company's Yates No. 1-A. It is located in Sec. 34½, Block 194, Pecos County, and was drilled into production in December, 1926, at a depth of 1,004 feet. The well was credited with an initial production of 350 barrels per day from that depth. The discovery of oil in this locality created considerable excitement, and immediately a rapid development began and continued until some time after the proration agreement among the operators of the Yates field was put into effect. To date, November 1, 1928, there have been 270 productive wells completed.[1]

LOCATION

The Yates field is in northeastern Pecos County, Texas, with the extreme easterly edge of the productive limits extending across Pecos River into Crockett County.

The nearest railroad is the K. C. M. & O. Railroad. The principal towns are Rankin and McCamey. Good, graded dirt roads connect the field with these supply points. Secondary roads also lead from the field to connect with the Old Spanish Trail Highway on the southwest.

Up to October 1, 1928, the productive area comprised approximately 15,800 acres[2] extending in a belt 4 miles wide from Pecos River northwesterly for a distance of 8 miles.

TOPOGRAPHY

The topographic expression within the Yates field is the result of stream erosion on the relatively low-dipping alternating hard limestone and shaly limestone beds of the surface Comanche rocks. The field is in the zone of erosion of Pecos River. The highest elevations are on the tops of the flat remnant mesas capped by hard lime beds, with the average highest elevations approximately 2,900 feet above sea-level. The

[1] Subsequent note: On July 1, 1929, 313 productive wells had been completed.

[2] Subsequent note: July 1, 1929, the productive area was 17,700 acres.

lowest elevations are in the alluvial filled valley of Pecos River, at approximately 2,150 feet above sea-level.

A characteristic feature of the topography is the presence of steep cliffs immediately below the cap of the highest mesas, some of these cliff-like faces being nearly 200 feet high. From the foot of these steep cliffs, the slopes emerge in bench-like expression into the bottoms of the narrow valleys. Such topography of sharp valley relief is a reflection, also, of the structure of the Comanche strata. In general, the remnant mesas seem to occupy the Comanche structural "highs"; hence, the drainage pattern gives some indication of the structure, in that the streams drain away from the "highs."

GEOLOGY

The geological formations involved in the Yates field comprise the surface strata belonging to the Comanche Cretaceous overlying at shallow depths Triassic "Red-beds." The Triassic unconformably overlies Permian beds consisting of alternating clastic sediments and anhydrite and of dolomitic limestones (the Permian "Big lime"). Production is obtained in the dolomitic limestones.

Surface mapping indicates that the Comanche Cretaceous strata have been folded into a large prominent domal structure overlying a more accentuated dome in the Permian rocks. This Permian structural "high" is on the southwest margin of the Saline Basin of West Texas. The general orientation of the elongate axis indicates that this field lies on the same general line of regional uplift, on this southwest margin, as the Crane County and the Upton County fields.

SURFACE STRATIGRAPHY

The surface rocks in the general area of the Yates field include strata of Comanche Cretaceous unconformably overlying a series of "Red-beds" supposedly Triassic. No proved Permian outcrops have been mapped within the area.

COMANCHE CRETACEOUS

Almost the whole surface of the Yates field is composed of Comanche strata, the lowest beds of which are known locally as the "Basement sands"—a basal sandstone of the Comanche for this part of Texas—lying unconformably on Triassic "Red-beds." This sand member is approximately 300 feet in thickness.

The "Basement sand" of the Yates field is very probably the equivalent of the Trinity sand; or, if not, it represents the basal member of the

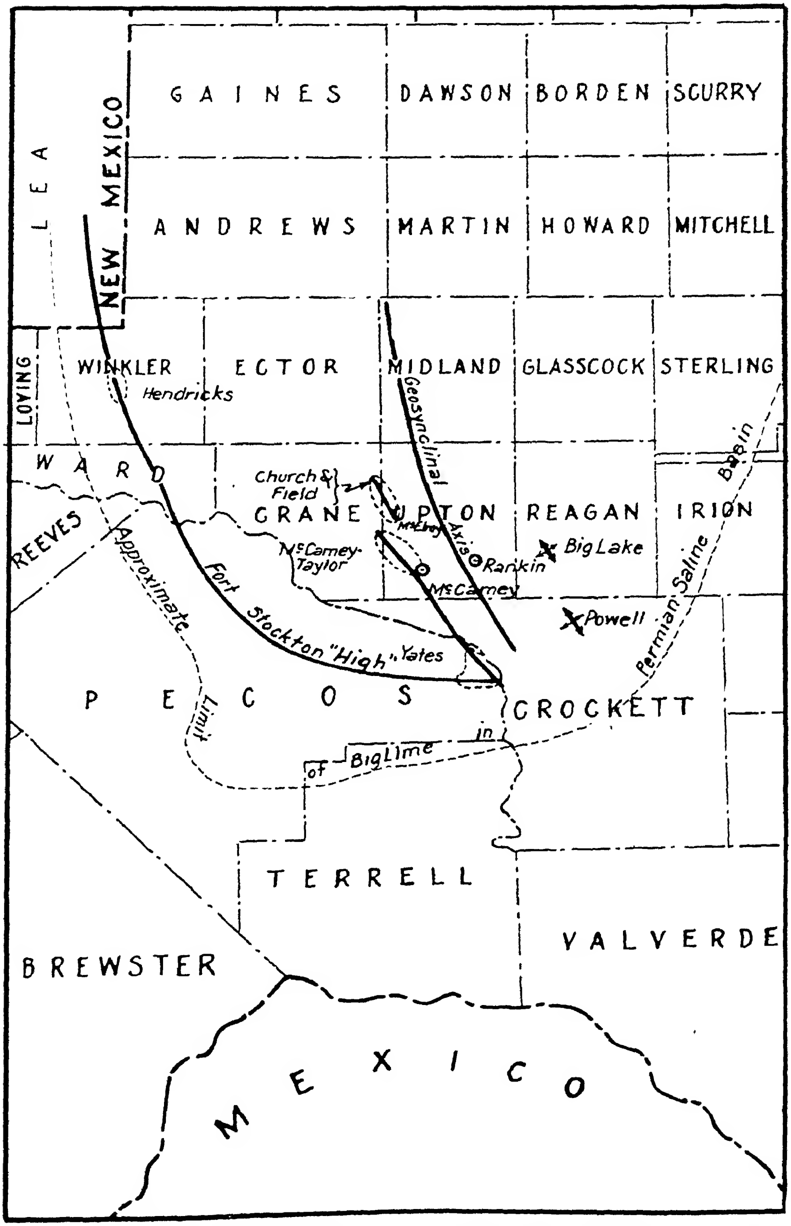


Fig. 1.—Sketch map of West Texas and southeastern New Mexico showing location of Yates field with respect to known major lines of anticlinal folding on the southwest margin of the Saline Basin of West Texas. Width of area mapped, approximately 150 miles.

Comanche series here deposited during the northerly encroachment of the Comanche sea over the irregular topography developed on the pre-Comanche land surface.

Immediately above the "Basement sand" a thin bed of hard yellowish-to-reddish-brown sandy limestone is present, with a rather uniform thickness ranging from 8 to 10 feet in the Yates field and adjacent areas. Wherever the "Basement sand" crops out, this bed was found; hence, owing to its constant presence and uniform thickness, it was used as a horizon-marker for detail mapping of the surface structure. Because of its stratigraphical position overlying the "Basement sand" and lithological similarity with the Walnut clay of central Texas, this marker, for the present purpose, has been correlated with the type Walnut clay member.

Above this Walnut clay follows an alternating series of gray-to-buff calcareous sandstone, argillaceous limestone, and calcareous shale attaining a maximum thickness of 560 feet. This series, for the purpose of geological structural mapping in this field, has been classed as undivided Georgetown, Edwards, and Comanche Peak limestones. Within this series certain horizons maintain persistent lithologic characteristics with sufficiently constant relations of intervals to serve as key horizons for structure mapping purposes. The surface structure map (Fig. 4) is based on elevations taken on these key beds reduced to the top of the "Basement sand" as datum.

TRIASSIC

So few isolated exposures of the Triassic "Red-beds" were found in the course of the field mapping that the description of this formation is reserved to the section on "Subsurface Stratigraphy."

PERMIAN

No exposures of rocks certainly assignable to the Permian were found at the time this dome was mapped. It later developed, however, following the careful microscopic work done by John Emery Adams, that a part of the "Red-beds" which had been assigned to the Triassic may belong to the Permian.

SUBSURFACE STRATIGRAPHY

The following description of the subsurface stratigraphy of the Yates field, taken from a report by Lon D. Cartwright, Jr., and John Emery Adams, is the result of an intensive scientific study of well samples.

Stratigraphic work in the Permian Basin of West Texas differs from that in other regions in that drillers' logs are entirely inadequate; fossils, both microscopic and macroscopic, are almost of no service; and readily recognizable

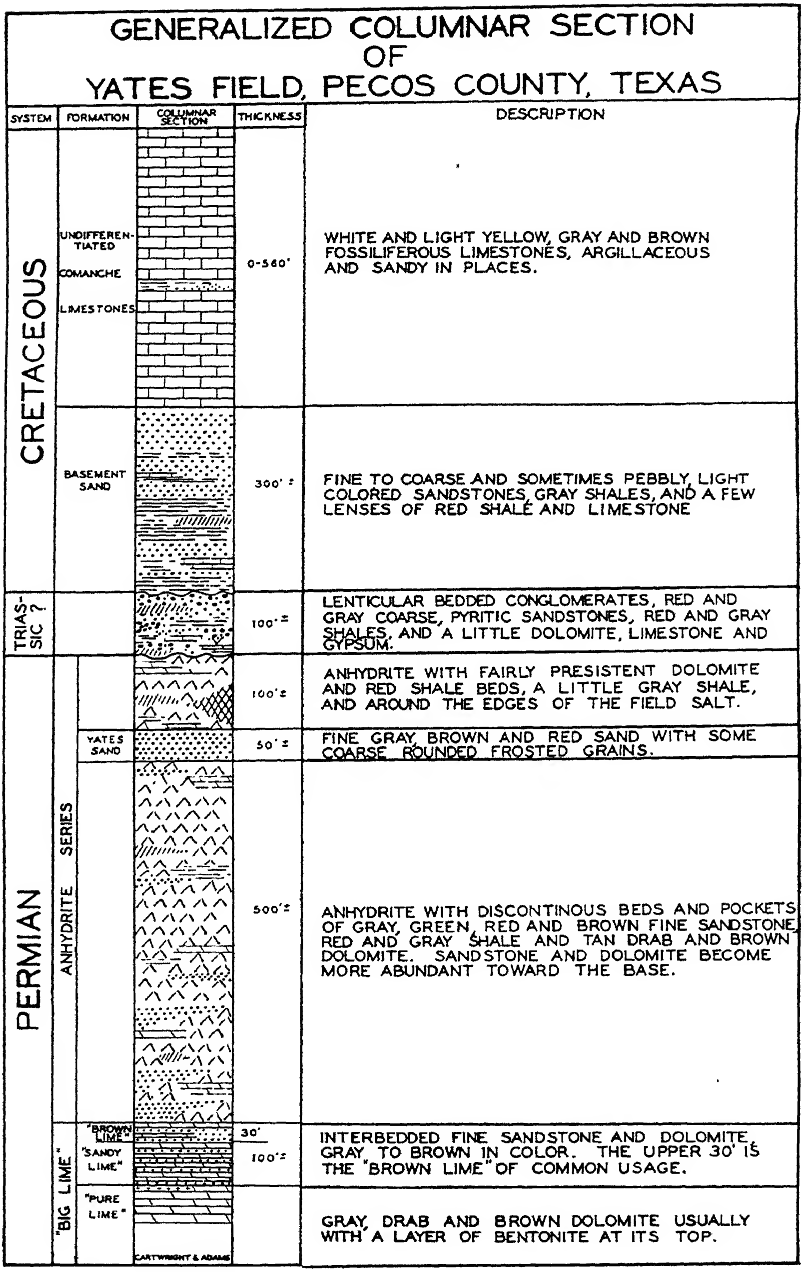


FIG. 2.—Generalized columnar section of geological formations in area of Yates field, Pecos County, Texas. Thickness in feet.

stratigraphic units of any constancy are rare. Dependence for correlation is placed on comparative lithology determined by careful examination of drill cuttings collected at close intervals. The study of the higher formations is considerably handicapped by the practice of most operators, especially in proved fields, of collecting samples of the lower part of the hole only. It has been possible in the Yates field, however, by examining the available complete and partial sets of samples, to interpret the stratigraphy. The staggered course of the two cross sections presented (Figs. 6 and 7) is due to the necessity of including wells from which the most complete sample sets could be obtained.

Formations representing three systems, Comanche, Triassic, and Permian, are encountered in the wells of the Yates field. All three are exposed in the general area. Comanche beds extend to depths ranging from 100 to 800 feet, the great differences in thickness being due to the irregular topography. They are underlain by a series of beds ordinarily about 100 feet thick which are assigned to the Triassic. Beneath these lies the Permian system, of unknown total thickness, which is penetrated in the field to depths ranging from 850 to 900 feet. The lower limit of penetration, within the productive limits of this field, has been arbitrarily fixed by agreement among the oil operators as 225 feet of the "Big lime." In addition to these formations, river sands and gravel cover the area on both sides of Pecos River and occur in the upper part of some of the wells.

The unconformity at the base of the Comanche is not sharply marked in the Yates field proper. Evidently the Comanche sea advanced from the south over an almost level surface. The Triassic has a rather uniform thickness in most of the field, but at the northern edge increases to 200 feet, and away from the field in that direction attains an even greater thickness. It was laid down as a terrestrial deposit over a gently-rolling post-Permian terrane, and the unconformity between it and the Permian is no more marked by irregularity than that between the Comanche and the Triassic.

COMANCHE

The Comanche beds in the Yates field area comprise two distinct units, an upper limestone and a lower sandstone and shale series. The limestone varies in color from white to gray and yellow. It is commonly fossiliferous, silicified in places, and sandy in the lower part. There is in many places a sandy and argillaceous zone about 200 feet above the Basement sand. No attempt has been made to divide the limestones in the wells. Thicknesses as great as 550 feet are penetrated, depending upon the location of the wells with respect to topography.

The sandstone and shale series is correlated with the Basement sand, which is the lowermost formation of the Comanche in West Texas. It ranges from 300 to 325 feet in thickness, which is greater than in other parts of the West Texas region, and is approximately divisible into an upper part consisting mainly of sandstone and less gray shale and a lower part consisting of gray shale with less sandstone and a little red shale. Both divisions contain a few beds of lime-

stone. It is possible that the upper is the "Basal sandstone" of Adkins[1] and the lower his "Basalmost Comanche (probably Trinity division)." Most of the wells encounter several water sands in the upper division and one in the lower. Gas and oil showings have been found in some wells, and the Gulf-Yates No. 8 produced some heavy oil, supposedly from this zone.

The sandstones of the Basement sand are white, yellow, brown, and gray, and range from fine to coarse and in places pebbly, with indication of a moderate degree of sorting. The grains are predominantly quartz, with a little chert, and range in shape from subangular to round, with the subround and round grains most plentiful. Calcareous matter is the most common cement, although the sandstones are ordinarily friable. The shales are light to dark gray in color, commonly finely sandy, and many exhibit colloidal properties. *Foraminifera* and fossil fragments can be washed from them, distinguishing them from the gray shales of the Triassic below.

TRIASSIC

Below the fossiliferous gray shales of the Comanche and above the anhydrite of the Permian, is a formation of heterogeneous composition which, because of its stratigraphic position and lithologic character, is correlated with the Triassic beds of adjacent areas. This formation is rather uniformly 100 feet thick on the crest of the structure, as indicated in the cross sections, and consists of quartz and chert gravels, red and gray non-fossiliferous shales, and a little limestone, dolomite, and gypsum. Much of the limestone and dolomite occurs as pebbles.

PERMIAN

The Permian section penetrated in wells in this part of the basin is generally divided into two parts, an upper evaporite and red-bed series, and a lower dolomitic limestone known as the "Big lime." The carbonate rocks of the "Big lime" are variously described as dolomites, dolomitic limestones, and magnesian limestones. They effervesce slowly in cold, dilute hydrochloric acid, and are totally consumed, except for impurities, when the acid is heated.

The Anhydrite series.—In the Yates field the upper division is known as the "Anhydrite series," and ranges in thickness from 650 to 750 feet. It consists of anhydrite, with much fine gray, green, brown, and red sandstone, and varying lesser amounts of gray and tan dolomite, red and gray shale, and around the margins of the field, salt. The beds of this part of the Permian are in general very lenticular, but there are several units in the Anhydrite series which have a rather uniform thickness and stratigraphic position. The most prominent of these is a 50-foot bed of sandstone here named the "Yates sand."[2]

[1] W. S. Adkins, "The Geology and Mineral Resources of the Fort Stockton Quadrangle," *Univ. of Texas Bull. 2738* (1927), p. 50.

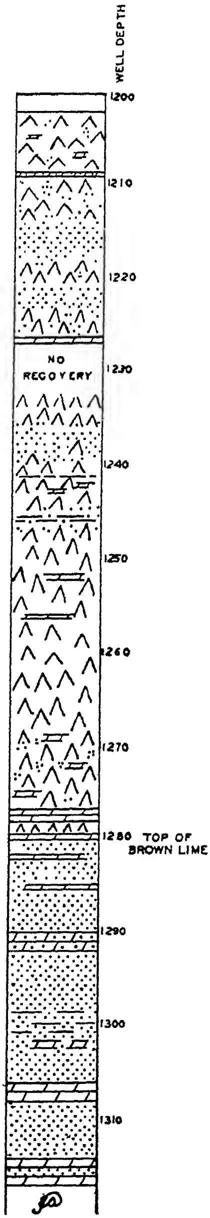
[2] This formation has been described before a meeting of geologists and discussed as the "Smith sand." As this name was found to be preoccupied, the name "Yates sand" is adopted.

The top of the Yates sand occurs from 100 to 150 feet below the top of the Anhydrite series, and from 500 to 550 feet above the top of the "Brown lime," the topmost member of the "Big lime" in this field. Toward the edges and away from the dome the intervals both above and below the Yates sand increase, as shown in the cross sections. Its position, away from the edges of the field, is immediately below the upper salt series.

The Yates sand is practically identical lithologically with the other Permian sands of the Yates field area. It is a fine-grained, gray, drab, or oil-browned quartzose sandstone, with anhydritic or dolomitic cement. It characteristically contains conspicuous, coarse, rounded, frosted quartz grains. Thin beds of gray shale, red shale, and dolomite are commonly associated with it. Oil and gas showings have been encountered in a great many wells in it, and salt water in a few. Its principal distinctive features are its stratigraphical position and its coarse frosted quartz grains.

That part of the Anhydrite series ranging from 100 to 150 feet in thickness overlying the Yates sand in the field consists of beds of anhydrite and gypsum with some dolomite, which enclose a fairly uniform layer of red shale. Toward the edges of the field this interval thickens, and salt beds appear in the section. Traced toward the north and east, these salts thicken and grade into the Upper Salt series of the Permian Basin. Between the Yates sand and the "Brown lime," the Anhydrite series consists principally of anhydrite, and contains some thin lenses of fine sandstone, similar to the Yates sand but with fewer coarse, frosted quartz grains. These sandstone lenses become thicker and more numerous near the base of the Anhydrite series. Interbedded with the anhydrite and sandstone are some thin lenses and pockets of dolomite, as mentioned in the description of cores from The California Company's Tippett 1–2–1, and a little red and gray shale.

The "Big lime."—Beneath the Anhydrite series in this part of the basin is a group of beds commonly referred to as the "Big lime." The "Big lime" of the Yates field is divided by most geologists into a thin upper member known as the "Brown lime" and a lower member of undetermined thickness known as the "Gray lime." Sample examination shows that there is a threefold division of the "Big lime" series in this locality, or, more concisely, two main divisions, the upper one of which is divided into two phases. The upper main division is the "Sandy lime," ranging from 100 to 125 feet in thickness, the topmost 30 feet of which is very sandy and characteristically browned with oil. This 30-foot member is the "Brown lime" of common usage. The lower main division is the "Pure lime," a non-sandy phase which has been penetrated for 100 or more feet in the Yates field. Many of the wells show a bentonite bed which is a fairly definite marker at the top of the "Pure lime" or in the base of the "Sandy lime." The "Sandy lime" is thicker in wells at the eastern extremity of the field, but sufficient samples have not been saved to define it there. The "Pure lime" is not shown in logs from this part of the field, either because the penetration has not been sufficient or because samples of the deeper parts were



Depth at Top, Feet	Depth at Bottom, Feet	Character
1,202	1,208.5	Anhydrite with small irregular pockets of gray and tan dolomite, and fine green sandstone
1,208.5	1,209	Very fine sandy brown dolomite
1,209	1,214	Anhydrite with 10 per cent shaly green sandstone and traces of tan dolomite
1,214	1,218	Fine green friable non-micaceous sandstone with thin beds of anhydrite containing some sandstone and undulating, tissue-thin, dolomite laminae. One 5-inch bed of sandstone contains plentiful coarse frosted quartz grains
1,218	1,220.6	Anhydrite with small irregularly bedded pockets of fine green sandstone grading down into intergrown masses of anhydrite and sandstone in equal amounts
1,220.6	1,223.3	Fine green sandstone
1,223.3	1,226.2	Anhydrite with 10 per cent sandstone in pockets which break across bedding rather than parallel it
1,226.2	1,227	Brown dolomite with inclusions of anhydrite grading down to anhydrite with vertical pockets of dolomite
1,227	1,232	No recovery
1,232	1,236	Anhydrite with undulating leaves of gray dolomite and vertical inclusions of fine gray sandstone in lower part
1,236	1,240	Fine green sandstone with few lenses of anhydrite
1,240	1,241 5	Anhydrite with green pyritic shale at base
1,241 5	1;245	Anhydrite with inclusions of tan dolomite, sandy at base
1,245	1,246.3	Bluish-green sandy shale
1,246.3	1,269	Anhydrite with 20 per cent sandstone in upper 1 foot and lenses of gray and tan dolomite below
1,269	1,276.8	Anhydrite with pockets of green sandstone and tan and gray dolomite
1,276.8	1,278	Highly porous, green and gray dolomite with anhydrite inclusions
1,278	1,279.5	Fibrous anhydrite with fibers developed normal to the dolomite contacts
1,279.5	1,280	Porous brown and green dolomite. Top of the "Brown lime"
1,280	1,290	Fine, platy, brown and gray sandstone with several thin beds of dolomite
1,290	1,292	Dense gray sandy dolomite
1,292	1,294	Porous gray granular dolomite
1,294	1,306	Platy to massive gray and brown sandstone; shaly from 1,298 to 1,301 and micaceous from 1,303 to 1,306
1,306	1,308	Dense gray and brown dolomite
1,308	1,314	Fine brown micaceous sandstone with 3-inch bed of dense gray dolomite
1,314	1,315	Finely porous white dolomite
1,315	1,316	Fine green sandstone
1,316	1,317	Gray, slightly porous dolomite, with plentiful pyrite crystals commonly occurring in narrow bands paralleling bedding

FIG. 3.—Graphical description of material recovered by coring in The California Company's Tippett Well No. 1–2–1, Sec. 2, D. F. Robertson Survey. Depths in feet.

not saved. The "Gray lime" includes the lower part of the "Sandy lime" and the "Pure lime."

The "Big lime" series of the Yates field consists of brown, drab, and gray dolomitic limestones, with some fine-grained, brown, drab, and gray sandstones in its upper division. The lithology of the dolomitic limestone as seen in drill cuttings seems about the same for all divisions, and cores taken so far are all from the upper or "Sandy lime." The undulating banded texture of some of the dense cores suggests that the material was deposited as a limy mud. Pre-solidification flowage is shown by the distortion of the fine black lines along the laminae. In texture the rock ranges from this fine mud type to coarsely granular and oölitic. Porosity occurs in the form of irregular solution cavities as large as $\frac{1}{16}$ inch in diameter, and in some places $\frac{1}{2}$ inch or more. These cavities are seen in some cores to form layers parallel to the bedding, and some are lined with dolomite crystals. In the granular phases there are very minute interstitial voids which also constitute porosity.

The original colors of the dolomitic limestone seem to have been light drab and light to medium-dark gray. Where rocks of the lighter colors have been permeated with oil, they are now brown. Few signs of fossils are to be observed in the drill-cuttings, but the cores show that some parts of the rock are distinctly fossiliferous and that other parts are barren. The forms are poorly preserved, but most of them seem to be small mollusks. A few ostracods and fusulinids have been detected in the cuttings by the writers, and it is reported that fusulinas have been identified in some fragments.

The sandstones of the Permian section are remarkably uniform from the lower part of the "Big lime" up through the Anhydrite series. They are characteristically very fine-textured and very well sorted, the grains ranging from $\frac{1}{12}$ to $\frac{1}{8}$ millimeter in diameter. A few sandstones both above and below the top of the "Brown lime" are even finer, with grains of $\frac{1}{20}$ millimeter. The grains are subangular in outline, but a few show considerable attrition and some frosting. In the Yates sand there are commonly well-rounded and frosted grains with an average diameter of $\frac{7}{10}$ millimeter, which probably represent an admixture of eolian sand. These are also found lower in the section, but less characteristically.

The composition of the sands is fairly uniform throughout, with the exception of differences in the content of white mica, which is found in some sands both above and below the top of the "Brown lime." Quartz is the most plentiful mineral, constituting more than 95 per cent of the grains. Dark-colored silicates of the heavy-mineral class comprise as much as 2 per cent of the grains. Pyrite is common in all the Permian sands, occurring both as a cement and as free crystals.

The top of the "Brown lime" is the horizon generally accepted for correlation. It may be defined as the first dolomitic limestone beneath the anhydrite in the western part of the field, and its depositional equivalent in the eastern part of the field. In the western part of the field—that is, in Section 35 and

west—the top of the "Brown lime" coincides with the base of the lowest anhydrite in the Anhydrite series. In the eastern part of the field there is more sand in the lower part of the Anhydrite series, and in some wells the anhydrite does not extend down to the top of the "Brown lime" but is separated from it by an intervening bed of sandstone, identical with that occurring in the Anhydrite series above and the "Sandy lime." An examination of the interval to the top of the Yates sand and with adjacent wells in which the Anhydrite does extend to the top of the "lime" shows that this intervening sandstone is a part of the Anhydrite series and not of the "Brown lime."

In the California Smith No. 3–35–11, shown in cross section *B-B′*, the anhydrite extends down to the top of the "Brown lime" but is interbedded with much sandstone in the lowest 25 feet. In the California Yates No. 13, 1,000 feet away, the base of the anhydrite is 25 feet above the top of the "Brown lime" and is separated from it by sandstone without interbedded anhydrite. An excellent correlation is established between these two wells based on the top of the Yates sand, the red shale above it, the prominent sand beds in the lower part of the Anhydrite series, and the top of the dolomite. This correlation shows that the 25 feet of sandstone and anhydrite immediately above the "Brown lime" in the Smith well is represented by the 25 feet of sandstone in the Yates well, and the base of the anhydrite varies by 25 feet.

In the Mid-Kansas Yates B-22, shown on cross section *A–A′* (Fig. 6), the base of the main anhydrite column is 125 feet above the top of the "Brown lime," and anhydrite forms only 6 per cent of the interval to the "Brown lime." In the Mid-Kansas Yates A-15, 600 feet south of B-22, the main anhydrite column extends down to within 30 feet of the top of the "Brown lime," with only about 10 per cent anhydrite occurring in the samples below it. If deposition of sand had gone a step farther at these two locations and no anhydrite had been deposited in the sands immediately above the "Brown lime," the base of the anhydrite would have differed stratigraphically by 95 feet. The Mid-Kansas G-1 and G-2 are examples of such complete replacement of the anhydrite by sandstone. In them 78 feet and 85 feet, respectively, of sandstone occur between the base of the anhydrite and the top of the "Brown lime."

A set of cable-tool cores was taken in The California Company's Tippett No. 1–2–1 at the northwest edge of the field from 80 feet above the top of the "Brown lime" to almost 40 feet below the top. These cores give a very good conception of this part of the stratigraphic section. Figure 3 is a graphic representation with accompanying descriptions.

STRATIGRAPHIC OCCURRENCE OF OIL AND GAS

Oil and gas are produced from the "Big lime," and, in some parts of the field, from the sands and dolomitic limestones in the Anhydrite series immediately above it. The top of the commercially productive zone is not a uniform horizon but ranges from 100 feet above the top of the "Brown lime" to 100 or more feet below it. This irregularity is well shown in cross section *A-A′* (Fig. 5).

California Yates No. 9 had a showing of oil approximately 90 feet above the top of the "Brown lime" but did not reach commercial production until it was 40 feet below the top. California Yates No. 10 and No. 15, offset wells, got commercial production 80 to 90 feet above the top of the "Brown lime" in the zone where No. 9 got its showing, and have not yet been drilled to the top of the "Brown lime." Similar, although less striking, variations are shown in many of the other wells in both cross sections. Commercial production in the Anhydrite series is limited to the eastern part of the field, the area in which it occurs practically coinciding with that in which there is much sandstone in the lower Anhydrite series. Most of the production of the field is from the highly porous dolomitic limestones of the "Sandy lime" and "Pure lime" series. Showings of oil and gas range through the Anhydrite series and into the Comanche. They are commonly found in the Yates sand and in the Triassic. It is possible that shallow production may be obtained from these zones when their development is justified.

DEPOSITION OF THE PERMIAN

The "Big lime" series is shown by its fossil content to be a deposit of normal marine waters. The overlying Anhydrite series is a desiccated sea deposit, which evidently lies conformably upon the shallow-water "Brown lime" phase of the "Big lime" series. Evidently normal, open-sea conditions existed in "Big lime" time, with a shallowing at its close during the deposition of the "Brown lime." During this shallowing, a barrier was raised which partly cut off the West Texas basin from the main ocean. Desiccation followed, with accompanying deposition of evaporites. Conditions were not static, and lenses of dolomite were deposited locally in the anhydrite.

Detritus from a constant source was being supplied the basin of deposition almost continuously from "Sandy lime" time through the deposition of the Anhydrite series. The supply was not affected by the change in composition of the sea water; therefore, the sandstones throughout this part of the Permian are of very similar lithology. Some of the clastics were laid down under oxidizing conditions, or were supplied in an oxidized state, and preserved as red beds. Part of the sands not now red may have been that color when originally deposited and have subsequently been reduced by hydrocarbons and accompanying hydrogen sulphide gas. The Yates sand is an example of this, for its correlative off the structure is normally red sandstone.

The area of the Yates field was probably a positive segment throughout Permian time, and remained high topographically. Thus a thinner evaporite and clastic section was deposited on it, while a thicker section containing many salt beds was deposited in the surrounding low areas.

SURFACE STRUCTURE

Detailed geological mapping in the area of the Yates field demonstrates that the Comanche strata have been folded from the original

attitude of deposition into a domal anticlinal fold by forces active during Comanche and post-Comanche time. The structural contour map (Fig. 4), which is largely the work of geologists of The California Company under the field supervision of Fred S. Wright, depicts the general nature

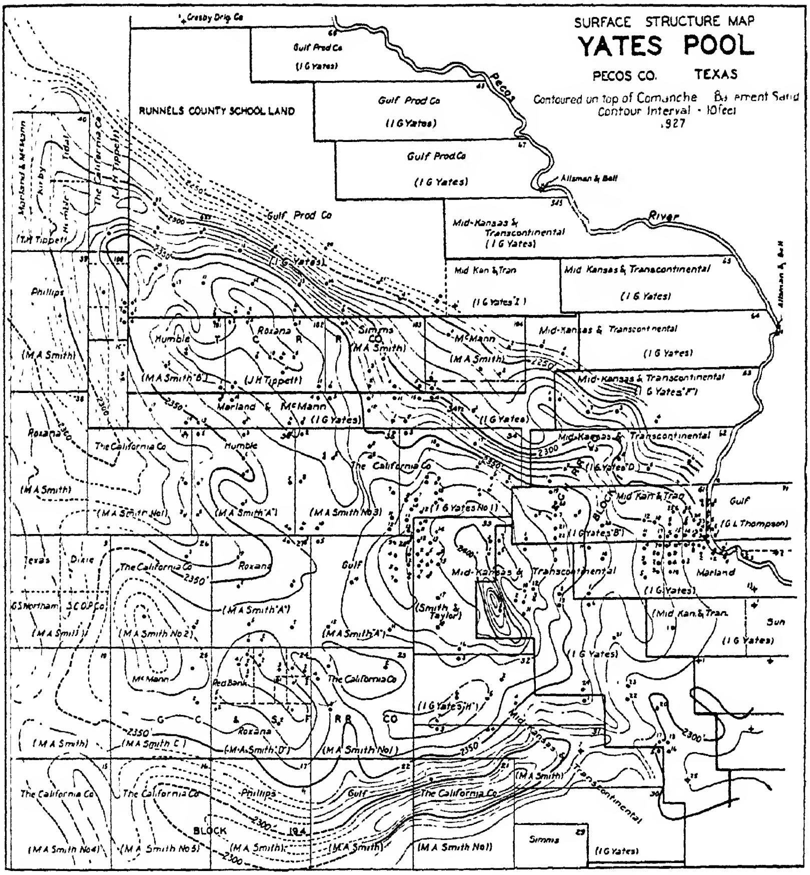


FIG. 4.—Surface structure of Yates field, Pecos County, contoured on top of Comanche "Basement sand." Contour interval, 10 feet. Width of area mapped, approximately 8 miles.

of the structure developed in these Comanche rocks. Elevations were determined on key horizons, and these were reduced to the topmost bed of the Basement sand as the datum on which the structural contours were drawn. Measurements of the intervals between this datum plane and the

key horizons at points within the area detailed indicate by variations in the intervals that some slight folding of these Comanche strata was progressive during Comanche time.

The salient structural feature (Fig. 4) is that of a domal anticline with the elongate axis extending generally northwest and southeast. The highest point of uplift is a small cross-folded, more-accentuated local dome, in the extreme west part of Scrap Section $34\frac{1}{2}$. From this local "high," a secondary anticlinal axis, less pronounced than the main northwest-trending axis, passes westerly through the north part of Sections 23, 24, and 25 and terminates in a local "high" with approximately 30 feet of closure in the south part of Section 26. On these two main axes, local "highs" are indicated by the elevations obtained.

The northeast flank of this surface fold is marked by a nearly uniform N. 60° W. strike with a northeast dip as steep as 4°. This uniformity of strike persists on this northeast flank from Pecos River in Sections 61 and 62, Block 1, H and GN, northwesterly through the Runnels County School Land Block into the northeast part of Section 40, Block 194. In this Section 40, the northwest plunge of the main axis is notable. Southwest of this main axis, a northwest-plunging syncline, starting in the north half of Section 27, Block 194, extends through Section 37 and becomes more prominent in Section 39, separating the main axis from the subsidiary axis on the south. South of this secondary uplift, a very pronounced syncline has been mapped through Sections 16, 17, 21, and 22, Block 194. This syncline is evidently closed, with the deepest part located in Section 21. The east side of the structure is defined by low easterly inclinations with some minor crenulations.

SUBSURFACE STRUCTURE

The accompanying map (Fig. 5) depicts, by the use of contours drawn on the top of the "Brown lime" as datum, the probable subsurface structure. This contour map indicates the presence of a domal fold in the Permian "Big lime" comparable with, but more accentuated than, the surface structure in the surface Comanche rocks. The Yates dome is a marginal fold on the southwest flank of the geosynclinal Saline Basin of West Texas and is evidently the southeasternmost "closed" fold on that same line of regional anticlinal uplift traceable northwest through the Crane County and the Upton County fields. The forces causing folds on this margin of the Saline Basin were evidently operative from the southwest; and it is certain that there is a correlative relation between the formation and development of this geosyncline, the Marathon fold, and the marginal lines of folds through Pecos, Crane, and Upton counties.

The Yates fold is an elongate eccentric dome with major axis oriented northwest and southeast. The highest area of uplift is a local dome developed on the major axis located mainly in the western part of Section $34\frac{1}{2}$, the northeast part of Section 33, and the south part of Section 34,

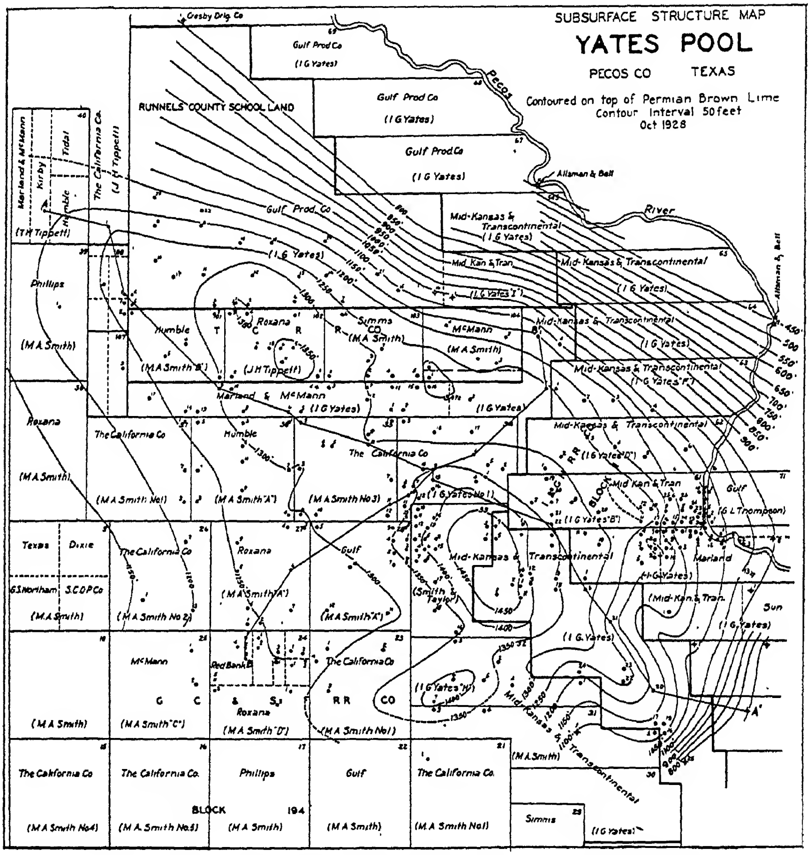


FIG. 5.—Subsurface structure of Yates field, contoured on top of "Brown lime" of the Permian "Big lime" series. Contour interval, 50 feet. Width of area mapped, approximately 8 miles.

Block 194. This "high" marks the bifurcation of the major and minor structural axes. Northwest from this area the axial area maintains a rather uniform elevation with minor crenulations, as far as the southwest part of the Runnels County School Land block, whence the axis trends more westerly, plunging more sharply west into Section 39, Block 194.

Southeast of this highest crest of the fold, a sharply folded anticlinal nose flanked on both the northeast and the southwest by sharp plunging synclines, plunges steeply southeast and marks the southeast termination of the Yates dome.

The minor axis branches off from the major domal axis in the extreme south part of Section 33 and seems to trend westerly through the central parts of Sections 32 and 23, Block 194. This secondary axis has been outlined only by a few wells; and this axis can be more closely delineated only by future developments (see Addenda).

The northeast and east flanks of this Yates fold are marked by a steep inclination of the "Brown lime," especially below the 1,250-foot structural contour, at least as far northeast as Allsman and Bell's River Bed Well No. 11. The structural interpretation shown in Figure 4 indicates a dip of approximately 450 feet to the mile along this flank. On the southwest flank, the dip is much less, being about 100 feet or less to the mile. Insufficient data preclude the definition of the south flank of the structure south of the minor east-west axis (see Addenda).

It is evident that the folding apparent in the surface Comanche strata is a reflection of folding of the Permian "Big lime." The major elongate axis of the dome in the subsurface rocks almost coincides with the position of the surface axis. The subsurface structure, however, is much more accentuated. It is, therefore, evident that the forces which caused the folding of the "Big lime" continued active during the Permian after the formation of the "Brown lime"; and, again in Comanche and post-Comanche, these caused the recurrence of uplift along the same axes.

Studies of subsurface conditions to date do not reveal evidences of faulting of any appreciable magnitude. But further developments may indicate some evidence of minor faulting, or fracturing, to admit of an explanation of the anomalous indications and even production of oil and gas from horizons above the main productive zones in the Permian "Big lime," as well as certain seemingly erratic structural conditions.

RELATION OF ACCUMULATION TO STRUCTURE

The accumulation of oil in the Yates field is evidently due to the presence of a domal fold in the Permian "Big lime," which fold has uninterrupted drainage from the synclinal basin on the northeast. The oil and gas have accumulated and have been reservoired in porous zones of the limestone. The porosity has very probably been the result of solution by acid waters. There is considerable variation in porosity, ranging from conditions that are almost capillary to conditions that are assumed

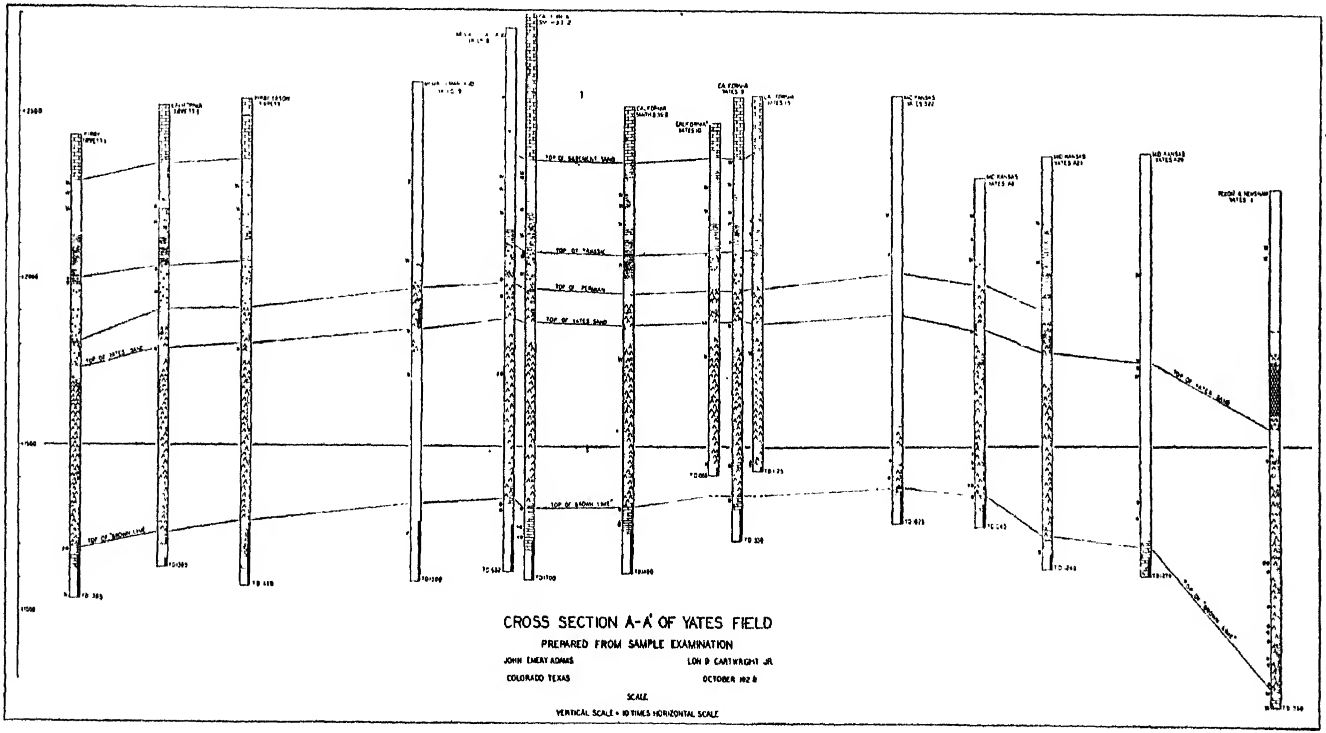


FIG. 6.—Northwest-southeast cross section through Yates field (Fig. 5), based on logs compiled from well cuttings. Depths in feet above sea-level shown in scale at left of section.

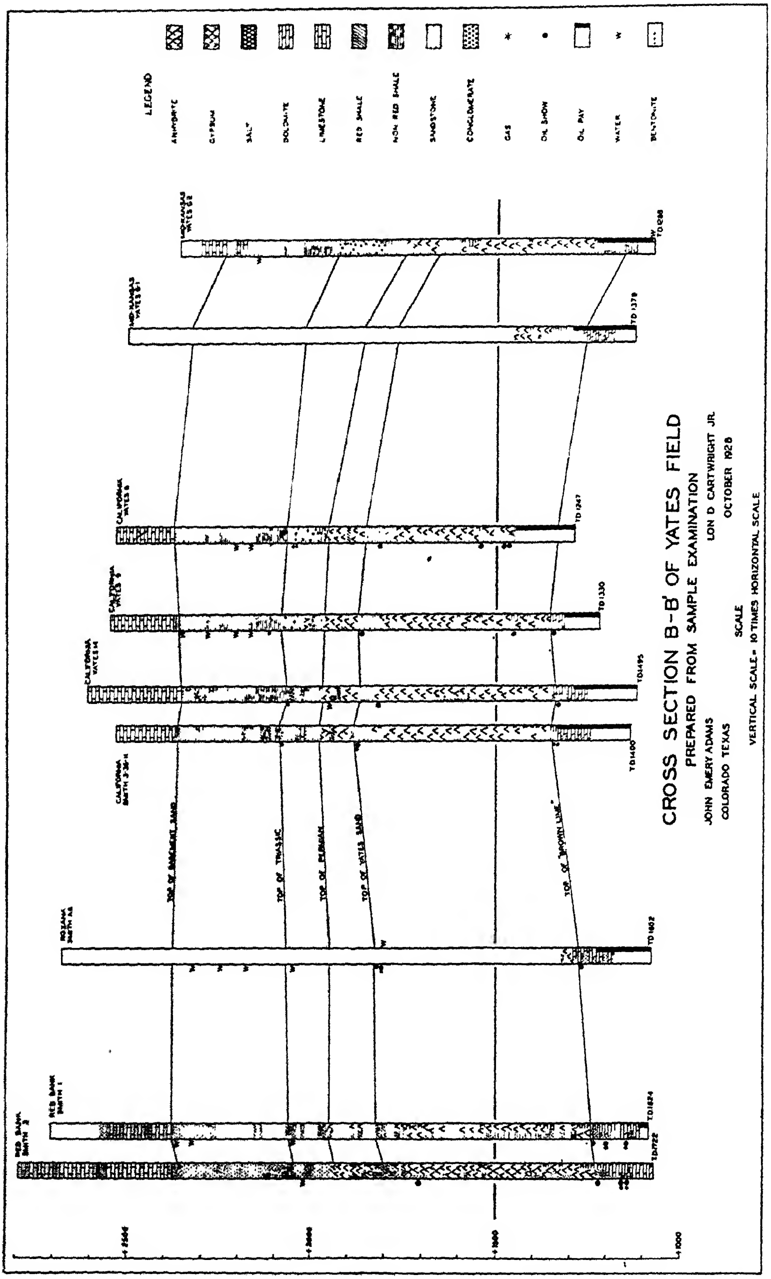


FIG. 7.—Southwest-northeast cross section through Yates field (Fig. 4), based on logs compiled from well cuttings. Depths in feet above sea-level shown in scale at left of section.

to be almost cavernous. Likewise, it is evident that there is wide vertical range as well as horizontal extent in the development of this porosity, for it has been demonstrated by the behavior of wells that the porosity is not parallel with the planes of stratification. Results of drilling indicate that sufficient oil has been stored in these porous zones to extend the probable productive beds approximately 350 feet structurally below the highest part of the fold. The results of drilling of wells low structurally on the flanks of this fold lead to the belief that the limit of production will closely approach the position of the 1,050-foot structural contour.

The inference from the behavior of edge wells in this field is that this body of oil is probably resting directly upon connate waters. There are evidently no impervious strata separating the oil from the water. However, the variation in the extent of porosity may eventually be an important factor in the behavior of water production.

The controlling factor in the prolific production of oil from the wells drilled into these reservoir rocks is the hydrostatic head with the gas of minor importance as an expulsive force. Generally, on the higher parts of the dome varying quantities of gas are encountered in sandstones, or within the limestones, above the oil. A few wells low on this fold have likewise found some gas.

ADDENDA[1]

SUBSURFACE STRUCTURE

Since November, 1928, when the manuscript for this article was submitted to the editor, additional wells which have been drilled in this field and in the immediately surrounding area, especially west and south of the productive area, have contributed data which define more closely the southern flank of this Yates dome. Recently completed wells in Sections 15, 16, 17, 21, and 22, Block 194, indicate the presence of a steep dip on the south flank of the Yates dome analogous to that on the northeast flank. Likewise, developments have tended to accentuate the minor axis of this structure and it is quite possible that this east-west trending axis may be a reflection and continuation of the Fort Stockton "high" (Fig. 1). If this proves true, it may be said that the Yates dome is located at the intersection of the east-west trending Fort Stockton "high" with the northwest-southeast line of folding which passes through Crane, Upton, and Crockett counties into Pecos County.

[1] July, 1929.

BIG LAKE OIL POOL, REAGAN COUNTY, TEXAS[1]

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Tulsa, Oklahoma

ABSTRACT

The Big Lake oil pool, located in the southwest corner of Reagan County, Texas, and opened by the discovery well in the Texon zone on May 28, 1923, was the first major oil field found in what is known as the "West Texas" district. The remarkable producing capabilities of its wells greatly stimulated geologic investigation and intense wildcat drilling throughout West Texas and southeast New Mexico. This has resulted in opening several prolific oil pools in a region formerly not considered seriously in estimates of our future petroleum reserves.

Four distinct oil zones have been developed in the field. Two, the Shallow and Texon, seem to belong in the Choza member of the Clear Fork formation, Permian in age. The Third and Fourth have been developed in the deep well (University 1-B) of the Texon Oil and Land Company at depths of 6,284–99 feet, and 8,520–25 feet, in probably the Strawn and the basal part of the Bend, respectively, both formations being Pennsylvanian in age, with the probability that the deeper zone is pre-Pennsylvanian. This well not only possesses an exceptional record for sustained rate of increase of daily oil production from the Fourth zone after drilling operations had ceased, but it is also the deepest oil-producing well in the world and the deepest boring ever drilled for any purpose. The well opened this Fourth oil zone on December 1, after the manuscript for the original paper had been submitted, on November 11, 1928, for publication; but a description of the well's producing activity and character of the oil from this deep zone is given in an Appendix under date of January 31, 1929.

The pool is closely related to a low anticlinal dome in the surface beds (Comanche), that is a reflection of a much more pronounced dome in the Upper salt beds (Permian) and a dome of still greater amplitude in the Texon discovery oil zone (Permian).

The pools in both the Shallow and Texon zones are encircled by edge water, thus conforming to the applications of the "anticlinal theory" of oil and gas accumulation. It is believed that the pool in the Texon zone has been trapped while the oil was migrating laterally up the dip from the west and northwest, and that the character of the oil and gas in the Shallow sand suggests they may have migrated upward from the Texon zone pool along the plane of the fault immediately on the east side of the dome. Further, it suggests that the source material of the oil and gas in the Texon zone is indigenous to the dolomitic limes of the Permian.

Up to October 1, 1928, the total production of the field was 36,238,451 barrels of oil—35,210,344 from the Texon zone and 1,028,107 from the Shallow sand, or 97.16 per cent and 2.64 per cent, respectively, of the total from the field.

Many new wells remain to be drilled to develop fully the proved leases for the Texon, Third, and Fourth zones.

INTRODUCTION

The Big Lake pool is an excellent example of oil and gas accumulation in water-bearing zones on structure of anticlinal or domal type. It cor-

[1] Presented by title before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, November 11, 1928.

[2] Chief geologist, Transcontinental Oil Company.

roborates in a remarkable manner the "anticlinal theory of oil and gas accumulation" first promulgated for practical application by I. C. White[1] in 1882 and published in 1885.

The pool (Fig. 1) is in the southwestern corner of Reagan County, Texas, on the Kansas City, Mexico, and Orient Railway, 15 miles west of the town of Big Lake and 90 miles west of San Angelo.

In the early stages of its development (April, 1926), it was described by Sellards and Patton[2] in a paper based on a microscopic and mineralogic examination of more than a thousand samples of drill cuttings from wells in the pool and adjacent region. Sellards and Patton's paper, which also contains information on the geologic conditions associated with the pool and the physical structure of the Texon "sand," or discovery oil zone, has been drawn upon freely by the writer of the present article.

Assistance has been rendered by R. J. Metcalf, P. M. Buttermore, and T. W. Leach, of the geologic staff of the Transcontinental Oil Company. Acknowledgments for well logs and production data are also due the officials and employees of both the Big Lake Oil Company and the Texon Oil and Land Company.

HISTORY

The Texon Oil and Land Company drilled the discovery well of the Big Lake pool, north of the present town of Texon (Fig. 6), on a solid block of land (68 sections, or 43,520 acres) owned in fee by the University of Texas. Later (October, 1923), the Big Lake Oil Company arranged with the Texon Oil and Land Company for the acquisition of 16 sections in this block, on which the Big Lake Oil Company now has its production. These two companies are the only operators in the Big Lake pool.

After drilling operations had been carried on for approximately two years by the Texon Oil and Land Company, the discovery well suddenly "blew in" on May 28, 1923, from a depth of 3,028 feet, flowing oil over the top of the derrick. The well was carrying water at the time from a zone higher in the hole, and all efforts to case off this water and put the well in good producing condition failed. In spite of this handicap the well flowed 75–80 barrels of oil daily, and shortly afterward, when put to pumping, made a daily average of 150 barrels of oil for several months, together with 8–10 barrels of water. This feature, together with the geologic structure of the immediate locality, as indicated by the Creta-

[1] I. C. White, *Science*, Vol. 5 (1885), pp. 521–22.

[2] E. H. Sellards and Leroy T. Patton, "The Subsurface Geology of the Big Lake Oil Field," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 365–81.

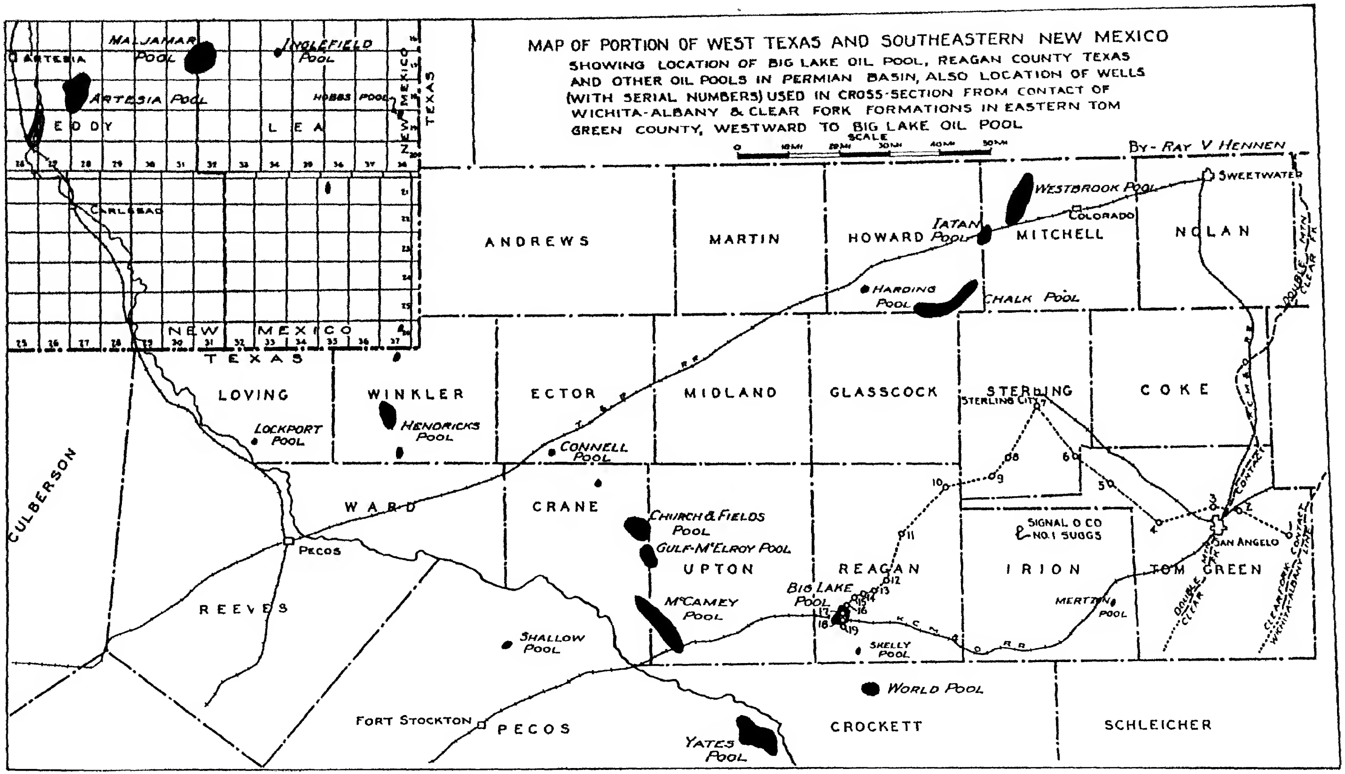


FIG. 1.—Part of West Texas and southeastern New Mexico, showing location of Big Lake oil pool, Reagan County, Texas.

ceous surface beds, strongly indicated that it was an edge well of a major oil pool and, on the recommendations of the writer, led to the acquisition of the 16 sections previously mentioned. At the time, the nearest test well that had been drilled for oil and gas to the horizon of the Big Lake lime was 28 miles away, and the nearest producing oil pool was the "Westbrook," of Mitchell County (Fig. 1), approximately 90 miles distant. For this reason little was known of the subsurface structural conditions of the Permian in Reagan and northern Crockett counties. The only structural information available for the Permian strata was the strong probability that the known, pronounced, northeast-southwest-trending structural terrace, in the surface (Cretaceous) beds, reflected more pronounced folding in the deeper Permian strata necessary to form the trap that the discovery well, by its producing capabilities, indicated was present.

Development followed rapidly by the two companies, and on March 1, 1925, there were 17 producing oil wells, from the Texon zone, with a daily production of 11,500 barrels. By January 1, 1926, there were 74 wells, making a total of 32,317 barrels daily. The peak, or highest single day's production for the pool, was 40,939 barrels, attained on August 31, 1925. On October 1, 1928, its daily production was 14,407 barrels.

PHYSIOGRAPHY

The whole of Reagan County is included within the Edwards Plateau province of Texas. At the site of the Big Lake oil pool, the surface presents a comparatively flat plain sloping gently northward from an elevation of approximately 2,750 feet above sea-level at the south edge of the pool to 2,660 feet at the north edge. This feature makes the construction of highways for drayage of material to wells from Texon (Fig. 6) comparatively inexpensive. Immediately south of the pool the surface is broken by a prominent northwest-facing escarpment (Fig. 3) of Edwards and younger limestone ledges, Comanche in age. The summit of this escarpment is more than 2,850 feet above sea-level. Drainage is toward the north and northeast into the waters of Middle Concho River.

STRATIGRAPHY

The thickness and character of the sediments of the Comanche, Triassic, and Permian systems in the Big Lake field have been so thoroughly described by Sellards and Patton[1] that they are not discussed here. Instead, a well log, typical of the formations encountered in drilling

[1] *Op. cit.*, pp. 368–77.

wells in the pool, is given (Table I). The log selected is that of the Big Lake Oil Company's University 137, in the northeast edge of the pool, Sec. 24, Block 9 (Fig. 6), inasmuch as it shows not only the horizons of both the Shallow and the Texon oil zones but also the Upper, Middle, and Lower salt beds (Fig. 2) in typical development, together with a clear definition of the top of the Big Lake lime. The log, as reported by the driller, with the exception of some additions in parentheses by the writer, is classified in harmony with the results shown in cross section (Fig. 2).

LOG OF DEEPEST WELL IN THE WORLD[1]

Through the courtesy of Frank T. Pickrell, president of the Texon Oil and Land Company, the detailed log of the deepest well in the world is given in this paper. This is Well 18 of the cross section (Fig. 2 and Table III). Its location is shown on Figure 6. In presenting the log of this well for publication, Mr. Pickrell explained that the well was not being drilled with the idea of making a record for depth, but rather for exploration purposes for oil horizons below the Texon zone. He said, further, that the well would be drilled as deep as possible, or until water was encountered or a bad fishing job caused them to stop. It will then be plugged back and the well made to produce, if possible, from the Third oil zone encountered at 6,284 feet, discussed on a subsequent page. This well produced oil from both the Shallow sand and the Texon zone. Later it was decided to make a deep test here. Its casing record is as follows: $15\frac{1}{2}$-inch—769 feet; $12\frac{1}{2}$-inch—1,820 feet; $10\frac{1}{2}$-inch—2,443 feet; $8\frac{1}{4}$-inch—2,454 feet; $6\frac{5}{8}$-inch—3,080 feet; and $5\frac{3}{16}$-inch—6,184 feet. Its elevation is 2,734 feet above sea-level.

At its present drilling depth (8,407 feet on October 30, 1928), there are 2,223 feet of open hole below the last string of casing. From the "pay" encountered at 6,284 feet, the hole filled several hundred feet with oil. This "pay" has continued to keep several hundred feet of oil in the hole as additional depth was attained, thus making it difficult to determine whether lower formations were petroliferous. Its log, with formations classified to top of Wichita-Albany, in harmony with the cross section (Fig. 2), and with some additions in parentheses, is shown in Table II.

In the log (Table II) the writer has tentatively placed the base of the Wichita-Albany (basal member of the Permian) at 4,860 feet, on the probability that the sandy phase from 4,605 to 4,860 feet, with oil showings, may represent the water-bearing sandy zone shown near the base of the

[1] See Appendix, pp. 533–41, for description of Fourth oil zone developed later in this well.

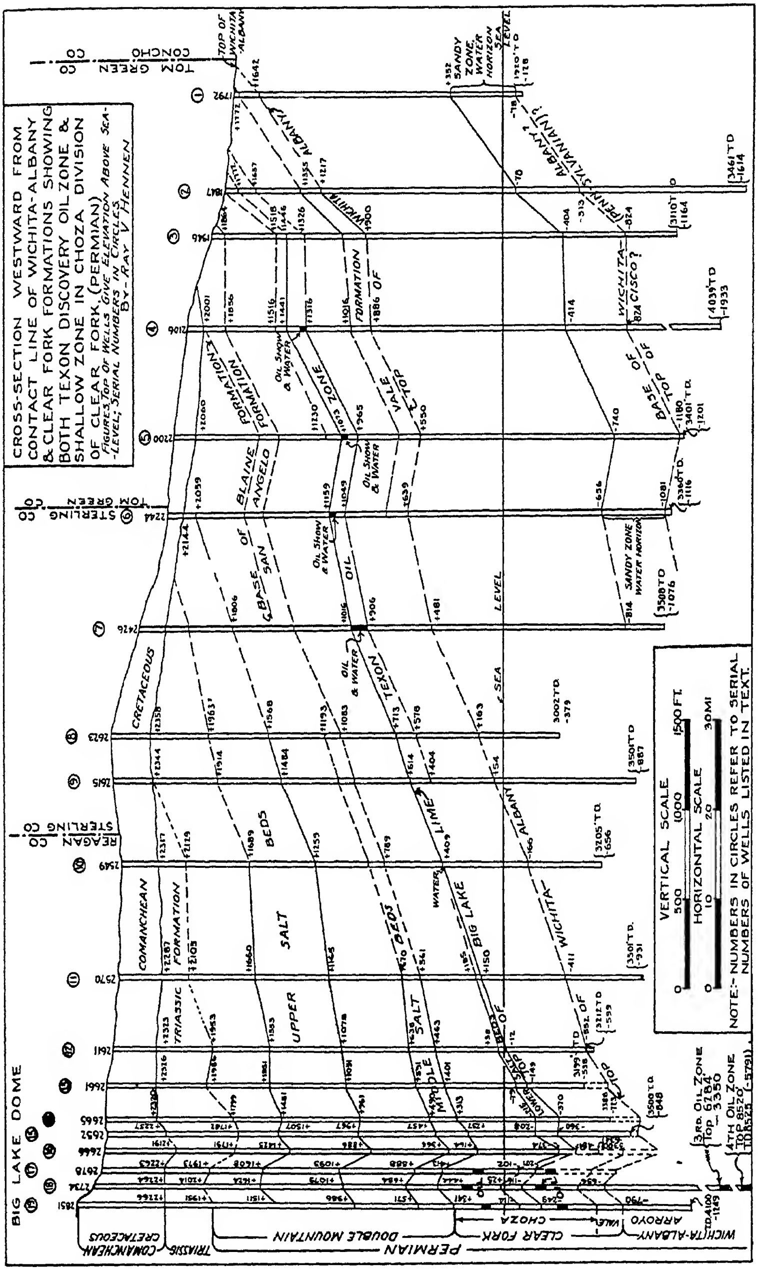


FIG. 2.—Cross section from surface contact of Wichita-Albany and Clear Fork formations (right) westward through Big Lake dome (left). Location of section shown in Figure 1.

TABLE I

Type Well Log, Big Lake Field

Big Lake Oil Company's University 137. Drilling commenced, February 1, 1928, and completed, March 20, 1928. Casing record: $15\frac{1}{2}$-inch—451 feet, 11 inches; $12\frac{1}{2}$-inch—673 feet, 4 inches; 10-inch—1,077 feet; $8\frac{1}{4}$-inch—2,569 feet; $6\frac{5}{8}$-inch—2,736 feet; $5\frac{3}{16}$-inch—2,892 feet, 10 inches. Elevation, derrick floor, 2,669 feet above sea-level. March 23, 1928, pumped 85 barrels oil, first 18 hours; 40 barrels, second 24 hours.

	Total Feet	Intervals Feet
Comanche (Lower Cretaceous) (345 feet)		
Edwards and Comanche Peak limestone		
Surface soil	30	
Lime, sandy	125	
Lime	200	200
Basement sands (145 feet)		
Sand—*Water*	280	
Red rock	310	
Lime	335	
Sand	345	145
Triassic (350 feet)		
Red rock	350	
Sand	360	
Lime	385	
Sand, red	410	
Red rock	465	
Sand—*hole full of water*	495	
Red rock	530	
Sand, red	560	
Red rock, sandy	590	
Lime	600	
Red rock	650	
Red rock, sandy	684	
Sand—*Water*	700	350
Permian (2,270 feet)		
Double Mountain formation (1,635 feet)		
Interval (378 feet)		
Red rock, sandy	850	
Shells and red rock	900	
Red rock	1,020	
Lime	1,030	
Red rock and shells	1,045	
Red rock, sandy	1,073	
Lime	1,078	378
Upper salt beds (567 feet)		
Salt	1,510	
Lime (anhydrite)	1,530	
Salt	1,645	567
Interval (360 feet)		
Red rock	1,670	
Lime (anhydrite) and salt	1,730	
Red rock	1,740	
Lime (anhydrite)	1,760	
Red rock	1,805	

TABLE I—*Continued*

	Total Feet	Intervals Feet
Interval—*Continued*		
Lime (anhydrite)	1,820	
Red rock	1,830	
Lime (anhydrite)	1,855	
Red rock	1,865	
Lime (anhydrite)	1,960	
Red rock	1,970	
Lime (anhydrite)	1,990	
Red rock	1,995	
Lime (anhydrite)	2,005	360
Middle salt beds (330 feet)		
Salt	2,110	
Lime (anhydrite)	2,120	
Salt	2,180	
Lime, broken (anhydrite)	2,220	
Salt	2,260	
Lime (anhydrite)	2,270	
Red rock	2,280	
Salt	2,335	330
Clear Fork formation (635 feet)		
Choza member (635 feet)		
Lime, sandy (anhydrite)	2,360	
Red rock, sandy	2,370	
Lime, sandy (anhydrite)	2,400	
Red rock, sandy	2,465	
Lime (anhydrite)	2,480	
Red rock	2,485	
Lime (anhydrite)	2,490	
Sand, red—*water*, 5 feet; Gypsum and lime, 2 feet; Sand, red, 8 feet } (Shallow oil zone)	2,505	
Red rock, sticky	2,515	
Shale, blue	2,520	
Red rock, sandy	2,575	
Lime (anhydrite)	2,585	
Lime, sandy (anhydrite)	2,595	
Red rock, sandy	2,630	
Sand, red, hard	2,655	
Lime (anhydrite)	2,665	
Sand, red, hard	2,670	
Sand, red (probably water-bearing, not recorded)	2,695	
Lime (anhydrite)	2,711	376
Salt, 19 feet; Lime, sandy (anhydrite), 10 feet; Salt, 75 feet; Anhydrite, 25 feet } (Lower salt beds)	2,840	129
Lime (Big Lake lime)	2,938	98
Oil "sand," 2 feet; Lime, 13 feet; *Oil "sand,"* 6 feet } (Texon oil pay zone)	2,959	
"Sand"	2,965	
"Sand"—*water*, 2965–70 feet	2,970	32

TABLE II

LOG OF DEEPEST WELL IN THE WORLD, TEXON OIL AND LAND COMPANY'S UNIVERSITY 1-B

	Total Feet	Intervals Feet
COMANCHE CRETACEOUS (480 feet)		
Surface, yellow	10	
Shells	60	
Gumbo	100	
Lime, hard, blue	150	
Lime, soft, white	300	
Sand—*water*	375	
Sand and red rock, broken	480	480
TRIASSIC (340 feet)		
Sand, red rock, broken	510	
Red rock, caving	548	
Sand—*water*	565	
Sand and lime	650	
Red rock	700	
Shale, sandy	720	240
PERMIAN (4,595 feet)		
Double Mountain formation (1,570 feet)		
Sand—*water* (4 barrels per hour)	765	
Red rock	825	
Sand—*water* (4 barrels per hour)	840	
Red rock	1,050	
Lime	1,070	
Red rock	1,110	
Salt (Upper)	1,655	
Red rock, caving	1,720	
Lime (anhydrite)	1,728	
Salt	1,740	
Red rock and shells	2,080	
Red rock and salt (Middle)	2,290	1,570
Clear Fork formation (1,100 feet)		
Sand, red and lime	2,360	
Lime (anhydrite)	2,380	
Sand and red rock	2,425	
Red rock	2,440	
Sand, red, 10 feet; Sand, hard, 12 feet; Sand, red, 18 feet } (Shallow oil zone)	2,480	
(400,000 cubic feet of gas at 2,461 feet; *oil showing*, 2,464 feet; *oil*, 2,469 feet)		
Sand, red	2,575	
Sand	2,580	
Shale	2,590	
Sand and lime	2,600	
Shells, sandy	2,630	
Red rock and sand	2,650	
Red rock	2,665	
Lime (anhydrite)	2,670	
Lime, gritty (anhydrite)	2,682	
Lime, gritty with sand	2,700	
Shale, sandy	2,710	
Shale	2,726	

TABLE II—*Continued*

	Total Feet	Intervals Feet
Clear Fork formation—*Continued*		
Lime (anhydrite)	2,740	
Shale	2,760	
Lime (anhydrite)	2,765	
Shale	2,770	
Lime (anhydrite)	2,820	
Lime and sand	2,840	
Sand and lime and shale	2,850	560
Lime (Big Lake)—gas, at 2,900–2,910 feet	2,900	
Sand and lime	2,920	
Lime, broken	2,950	
Sand, shells, and shale	2,980	
Lime, sandy—Second *oil "pay,"* Texon	3,020	
Shale, sandy	3,050	
Shale, dark	3,070	
Lime	3,095	
Lime shells, broken	3,148	
Lime, hard, gray	3,165	
Lime, gray	3,190	
Lime, hard, gray	3,290	
Lime	3,306	
Slate	3,316	
Lime shells, broken	3,340	
Lime shells	3,360	
Sand	3,370	
Lime	3,375	
Shale	3,390	540
Wichita-Albany formation? (1,470 feet)		
Lime	3,395	
Lime, sandy	3,400	
Lime	3,410	
Lime, black, sandy	3,420	
Sand—*water*	3,470	
Sand, hard	3,482	
Lime	3,513	
Shale	3,545	
Lime shells	3,560	
Shale	3,610	
Lime	3,654	
Shale	3,690	
Sand	3,710	
Lime	3,718	
Shale	3,730	
Lime, sandy	3,766	
Shale, sandy	3,778	
Lime	3,788	
Lime, sandy	3,834	
Shale	3,882	
Shale, sandy	3,910	
Sand	3,918	
Shale	4,216	
Sand	4,230	
Shale	4,505	
Sand	4,515	

TABLE II—*Continued*

	Total Feet	Intervals Feet
Undifferentiated—*Continued*		
Lime, black, hard	6,820	
Lime shell, hard	6,825	
Shale, black	6,840	
Lime shell, hard, black	6,845	
Lime, gray, sandy, medium	6,860	
Lime, black	6,885	
Lime, black, hard	6,895	
Lime, medium, black	6,945	
Lime, black, harder than ordinary	6,955	
Lime, medium, black	6,985	
Lime, hard, black	7,005	
Shale, black, soft	7,220	
Lime, black, hard	7,230	
Slate, black, medium	7,250	
Lime, black, hard	7,275	
Lime, shell, hard, black	7,290	
Lime, black, very hard	7,545	
Lime, black, extra hard	7,580	
Lime, hard, black	7,590	
Lime, hard, gray	7,660	
Lime, hard, black, sandy	7,670	
Lime, hard, black	7,685	
Lime, hard, black, sandy	7,820	
Lime, hard, black	8,180	
Slate, black	8,225	
Lime, black	8,245	
Lime, black, hard	8,273	
Lime, gray	8,281	
Lime, black	8,285	
Lime, gray	8,290	
Lime	8,308	
Lime, black	8,324	
Lime, hard, black	8,335	
Lime, black	8,337	
Lime, gray	8,340	
Lime, black ("flowed 80 barrels oil from upper 'pay'")	8,343	
Lime, black	8,407	
Lime, black	8,480	
Lime, black, sandy	8,482	
Lime, black, sandy—*oil and gas*	8,490	
Lime, gray, hard, sandy—*oil and gas*	8,516	
Lime shell, black	8,520	
"Sand"—*big gas and oil "pay"* (Fourth oil zone)	8,525	2,241

Wichita-Albany in Wells 1–6, inclusive, of the cross section (Fig. 2). The sand, or Third oil zone of the Big Lake field, at 6,284–99 feet, probably belongs in the Strawn (Pennsylvanian). Below 6,730 feet, black shale and black lime predominate and may represent the Bend formation (Penn-

sylvanian) as classified by Plummer and Moore[1] for north-central Texas. The bottom of the hole is believed to be in pre-Pennsylvanian rocks.[2]

DISCUSSION OF CROSS SECTION (FIG. 2)

Much controversy exists among geologists familiar with the stratigraphy of West Texas, as to the correlation of the Big Lake lime, 50–100 feet below the top of which occurs the Texon "discovery" oil zone of the Big Lake pool. Some contend that it belongs in the Double Mountain formation (Permian in age), while others are inclined to its inclusion in the Clear Fork (Permian). The writer favors the latter conclusion largely because of the evidence presented in the cross section (Fig. 2).

In making this cross section, the detailed logs of 19 wells were used. These wells are numbered serially from 1 to 19, inclusive, westward to the Big Lake pool. The same set of serial numbers is used to designate the wells in Figures 1 and 2. The list of wells (Table III) accompanying the cross section (Fig. 2) has the same serial numbers to designate the wells, and gives their ownership, names, and location in order.

By referring to Figures 1 and 2, it will be noticed that Wells 1 and 2, in eastern Tom Green County, are located on the outcropping edges of the Clear Fork formation where the latter has been recognized and defined; and that the contact line between the Clear Fork and the immediately overlying San Angelo formation (basal member of the Double Mountain) passes between Wells 2 and 3, thus facilitating accurate determination of the position of the base of the Double Mountain in Well 3. In Well 1, the Vale formation (basal member of the Clear Fork) is definitely recognized, thus accurately fixing in it the position of the top of the Wichita-Albany formation. By using the water-bearing sandy zone shown near the base of the Wichita-Albany (Fig. 2) as one of the aids in correlation, it is believed that the top of the latter is correctly placed in Wells 1–7, inclusive, and likewise the base of the San Angelo formation.

[1] Frederick B. Plummer and Raymond C. Moore, "Stratigraphy of North-Central Texas," *Univ. of Texas Bull. 2132* (June 5, 1921), Table I, facing p. 22.

[2] F. A. Bush, paleontologist for the Sinclair Oil and Gas Company, at Tulsa, Oklahoma, reports finding very primitive *Fusulinid* forms in the cuttings from this well (University 1-B) from 5,700 to 6,500 feet, or *Triticites*, sp., that strongly indicate beds of Pennsylvanian age. In the Suggs No. 1 well of the Signal Oil Company, recently completed in northern Irion County (Fig. 1), he also reports characteristic marine fossils as plentiful in the cuttings from the Wichita-Albany, and, because of this evidence, places the top of the latter at a depth of 1,855 feet in the Suggs well, and the base of the San Angelo (Double Mountain) at a depth of 1,370 feet, or at practically the same interval below the base of the Upper salt as shown for Wells 8 and 9 of the cross section (Fig. 2).

TABLE III

List of Wells Used in Cross Section (Fig. 2)

(Serial numbers for wells same as used in Figures 1 and 2)

Serial No.	Company	Well	Location
	TOM GREEN COUNTY		
1	Fitzgerald and Talliferro	Bennett 1	Cent. SW. ¼, Sec. 1628, Behringer Survey
2	J. W. Marland.........	Johnson 1	Cent. SW. ¼, Sec. 6, R. B. Sanderson Survey
3	Fannin Oil Company	Harris 1	Sec. 170, W. C. R. R. Co. Survey
4	World Oil Company....	Pulliam 1	Sec. 18, Block 4, H. & T. C. Ry. Survey
5	Penn and Windsor......	Turner 1	Sec. 60, Block 5, H. & T. C. Ry. Survey
	STERLING COUNTY		
6	Kanawah-Angelo	Clark 1	Sec. 6, Block A, G. C. & S. F. Ry. Co. Survey
7	Ohio-Tex.............	Durham 1	SW. ¼, Sec. 18, Block 12, T. & P. Survey
8	C. J. Wrightsman.......	F. G. Howard 2	Sec. 2, Block A, G. C. & S. F. Survey
9	C. J. Wrightsman (Fidelity Oil Company)....	Geo. R. Hull	Survey 6, Block A, G. C. & S. F. Survey
	REAGAN COUNTY		
10	Texas Company........	Suggs 2	Cent. Sec. 87, Block 2, T. & P. Ry. Co. Survey
11	Simms Oil Company....	Sawyer well	Sec. 12, S. A. Glass Survey
12	Zoch..................	Tally 1	Cent. NE. ¼, Sec. 5, G. C. & S. F. Ry. Co. Survey
13	Gulf Production Company...............	University 1	Sec. 28, Block 58
14	Hughes...............	University 1	SW. cor., SE. ¼, Sec. 5, Block 9
15	Crockett Drilling Syndicate...............	University 1	NW. cor., SW. ¼, Sec. 9, Block 9
16	Pilot Oil Company.....	University 1	NW. of SW., Sec. 11, Block 9
17	Big Lake Oil Company..	University 1	SW. cor., Sec. 24, Block 9
18	Texon Oil and Land Company...............	University 1-B	NW. cor., SW. ¼, Sec. 36, Block 9
19	California Oil Company.	University 1	NW. cor., NE. ¼, Sec. 13, Block 8

After the completion of Figures 1 and 2, it was found in comparing the log of Well 6 with the log of Well 65 of Plate 14, accompanying *Bulletin 780-B* of the U. S. Geological Survey, that Hoots[1] tentatively places the base of the Double Mountain formation approximately 430 feet higher in the rock column than shown on Figure 2. This last-mentioned well is located only 3 or 4 miles southwestward from Well 6. In other words, Hoots places the base of the Double Mountain at approximately the position that the base of the Upper salt beds (Fig. 2) should occupy. Should his correlation be correct, then it will be readily seen, in the face of the evidence presented by Wells 7–19, inclusive, how much more difficult it is to include the Big Lake lime in the Double Mountain formation.

By reversing the process and working eastward from the Big Lake dome, where the position of the top of the Big Lake lime in the rock column is definitely known regardless of its age, it will readily be observed (Fig. 2) that the Permian sediments immediately overlying the lime in question, up to the base of the Triassic, carry three very important markers for correlation purposes. These are the Upper, Middle, and Lower salt beds. The last mentioned, in the Big Lake pool, immediately overlie the Big Lake lime. The three salt beds in question are easily recognized in the wells from No. 19 eastward to and including No. 11, and the base of the Upper salt bed eastward from Well 10 to Well 6. The cross section, therefore, indicates that the base of the San Angelo formation is closely correlated with the base of the Middle salt beds.

A rather pronounced anticlinal nose, based on subsurface data in wells drilled for oil and gas, extends northwestward to and beyond Sterling City from the area a short distance north of San Angelo. This structural feature plunges northwestward. Wells 4–7, inclusive, are located on this anticlinal fold. It is seen on the cross section (Fig. 2), that the four wells last mentioned carry showings of oil and water immediately below the top of what has been correlated as the "Big Lake lime" and as the "Texon oil zone."

A careful consideration of the foregoing data indicates very strongly that this petroliferous horizon, in the wells last mentioned, is to be correlated with the Texon discovery oil zone in the Big Lake pool, and that both the oil-producing zones of the Big Lake pool belong in the Choza division of the Clear Fork and have been so classified at the left margin of the cross section (Fig. 2).

[1] H. W. Hoots, "Geology of a Part of Western Texas and Southeastern New Mexico," *op. cit.* (1925).

In this part of the state it is difficult to obtain, from well cuttings of either the Double Mountain or the Clear Fork sediments, reliable fossil evidence for age determination. Besides, many of the wells between the Big Lake pool and the outcrop of the contact between the Clear Fork and Wichita-Albany formations were drilled several years ago when such care as now prevails for the West Texas region was not taken in the description of formations and collection of well cuttings for study. The classification, as tentatively shown on the cross section (Fig. 2), has been made entirely from a study and comparison of the logs of the wells exhibited thereon, many of which fail to differentiate between anhydrite and limestone and it is submitted for what it may be worth as an aid in determining the facts until more carefully kept logs become available from wells in the region between eastern Tom Green County and the Big Lake pool. It may be significant that the Big Lake lime is dolomitic in character and that the Choza division of the Clear Fork, at its eastern outcrop, carries several dolomitic beds.

UNCONFORMITIES

Two marked unconformities, and probably a third, local in extent, are present in the strata of Reagan County between the surface and the horizon of the Texon zone.

The *first*, in descending order, is very pronounced and occurs at the contact of the Comanche and the Triassic (Fig. 2).

The *second* is at the contact of the Triassic and the Double Mountain formation (Fig. 2). Because of the marked similarity of the sediments both in color and general physical appearance, as revealed in the cuttings from wells, it is very difficult to place the contact of the Triassic and the Double Mountain. In the cross section (Fig. 2), its position is substantially correct.

The *third* is at the contact of the Lower salt beds (Fig. 2) with the Big Lake lime. The presence of an unconformity immediately over the Big Lake lime is indicated by the non-uniform thickness of the salt bed in question, with its associated anhydrite, in wells drilled within the oil pool, this thickness ranging from almost nothing to more than 100 feet. It may be local for the Big Lake dome.

CONDITIONS OF DEPOSITION

From the prevalence of salt beds and anhydrite in the Permian, from the base of the Triassic down to the top of the Big Lake lime, in Reagan and several other West Texas counties, it is quite evident that the deposition of this part of the rock column took place in an inland sea in the

West Texas region during Permian time—a sea whose southwest communication with the ocean had been cut off. This outlet to the sea was evidently open during deposition of the Big Lake lime and underlying beds down to the present depth (8,407 feet) in Well 18 (Figs. 1 and 2).

COMPETENCY OF BEDS

With the exception of the Triassic, Double Mountain, and the upper half of the Clear Fork beds, which are softer and weaker material, the sediments at the Big Lake pool contain many heavy limestones and dolomitic beds capable of offering strong resistance to thrust forces, either of tangential or vertical type. This is especially true for the Wichita-Albany and the lower half of the Clear Fork formations. No evidence, thus far, has been found of buckling or thrust faulting on the east flank of the Permian basin of West Texas.

STRUCTURE

REGIONAL AND LOCAL FOLDING

A broad, but comparatively low, structural basin is present in the West Texas area, usually referred to as the "Permian basin." That this syncline exists has been proved by the wide distribution of great thicknesses of salt and anhydrite which must have occupied the lowest parts of the basin. The Permian beds east of the High Plains area have a regional west dip of 30–35 feet to the mile; and those west of the High Plains dip eastward at a slightly more rapid rate, or 40 feet, as near as can be determined from data revealed in well logs.

The Big Lake dome is on the southeastern slope of this great structural basin. This slope is interrupted at intervals by northwestward-plunging anticlinal noses. Subsurface data from wells indicate that the Big Lake dome is a local structural feature on one of these northwest-plunging anticlines, whose axis evidently passes through both the World pool of Crockett County (Fig. 1) and the Big Lake dome.

DETAILED STRUCTURE ON SURFACE (CRETACEOUS) BEDS (FIG. 3)

The structural attitude of the surface beds, Comanche (Lower Cretaceous) in age, at the Big Lake pool, reflects only in a slight way the subsurface anticline last mentioned. It does show, however, the presence of a low dome with a marked northeast-southwest elongation.

Figure 3, in addition to showing the approximate limits of the Big Lake pool, gives contours of the elevation above sea-level of the top of a "key rock" in the surface beds (Cretaceous). This key bed is a limestone, ranging from 5 to 10 feet in thickness, that is found 20–30 feet down in a

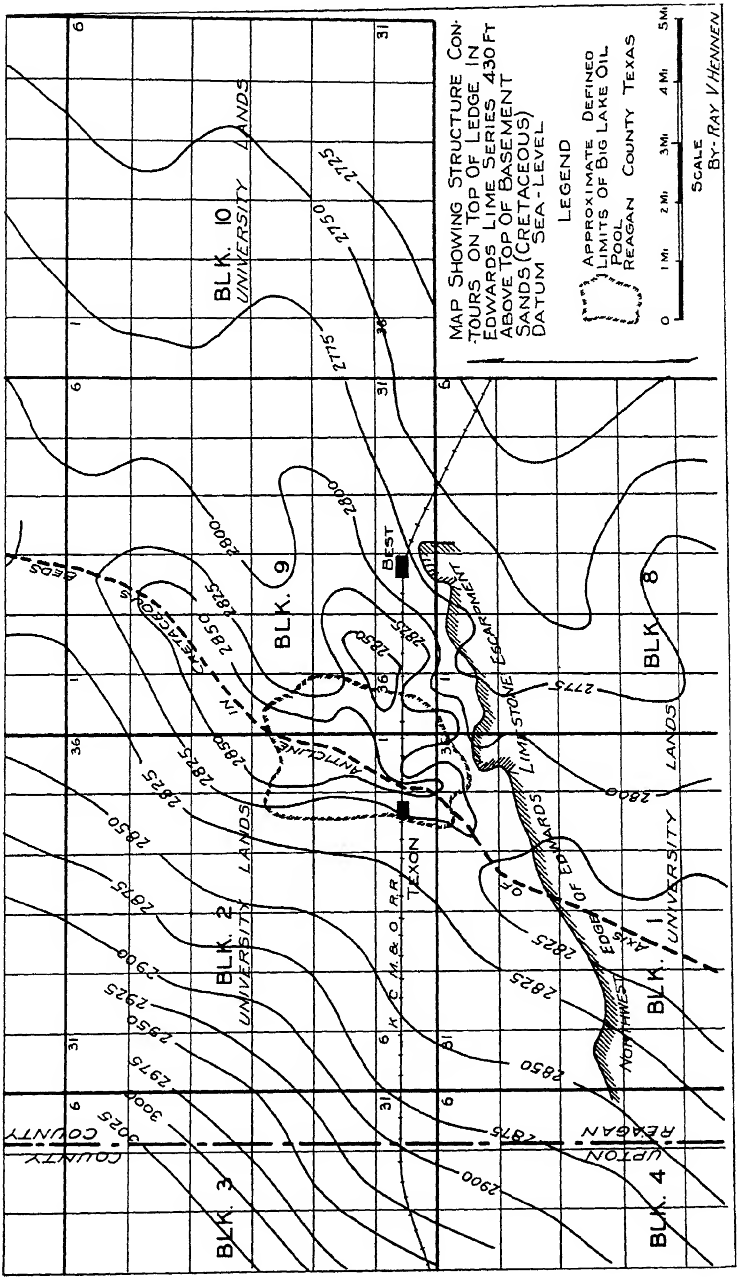


FIG. 3.—Structure of Big Lake dome and vicinity, contoured on top of ledge in Edwards limestone series 430 feet above top of Basement sands (Cretaceous).

soft, white, very fossiliferous and marly division of the Cretaceous limes. This marly division, ranging from 150 to 175 feet in thickness, is immediately overlain by a heavy limestone, 25–50 feet in thickness, that is known throughout Reagan, Crockett, and Pecos counties as the "cap rock." The base of this marly division was encountered in the Big Lake Oil Company's Well No. 3 at a depth of 35 feet. This is important in that it makes possible a definite determination of the interval from the top of the key bed down to the top of the Basement sands on the immediate site of the Big Lake pool where surface beds are concealed. This interval was found to be 430 feet, and it was used at wells for contour purposes.

Southward from the Edwards limestone escarpment (Fig. 3), elevations of the key bed where determined by plane-table survey during 1923 by K. H. de Cousser under the supervision of A. M. Hagan and the writer. Northward from this escarpment, its elevation was found by adding its interval (430 feet) to the elevation of the top of the Basement sands, as revealed in the logs of the many wells drilled in the Big Lake pool and the adjacent region.

If the low regional southeast dip (10–15 feet to the mile) of the Cretaceous is considered, this dome, closely related to the Big Lake pool, with a closure of approximately 30 feet, is a pronounced reflection of the subsurface dome in the underlying Permian beds. It has its greatest elongation northeast and southwest; but on its south half, at the site of the Big Lake pool, there is evidence of northwest-southeast elongation.

SUBSURFACE STRUCTURE

Contours on anhydrite bed in Upper salt beds (Fig. 4).—Figure 4, in addition to exhibiting the approximate area of the Big Lake pool, gives contours showing the elevation of the top of an anhydrite bed, 20–40 feet in thickness, that belongs approximately 400 feet down in the big or Upper salt beds (Fig. 2) and generally 100–125 feet above the base of the same salt beds. In determining the structural attitude of these salt beds, it was found much more practicable to use this anhydrite stratum rather than the top of the salt, for the reason that it is everywhere present and much more easily recognized by drillers in southwestern Reagan County than the exact top of the Upper salt series. Figure 4 embraces a considerable area surrounding the Big Lake pool; and on it the elevation of the key rock is shown, not only from data revealed by wells within the pool but also by wells in the surrounding region. Outside the pool, figures associated with dry holes and preceded by a plus sign, give the elevation above sea-level for the key rock.

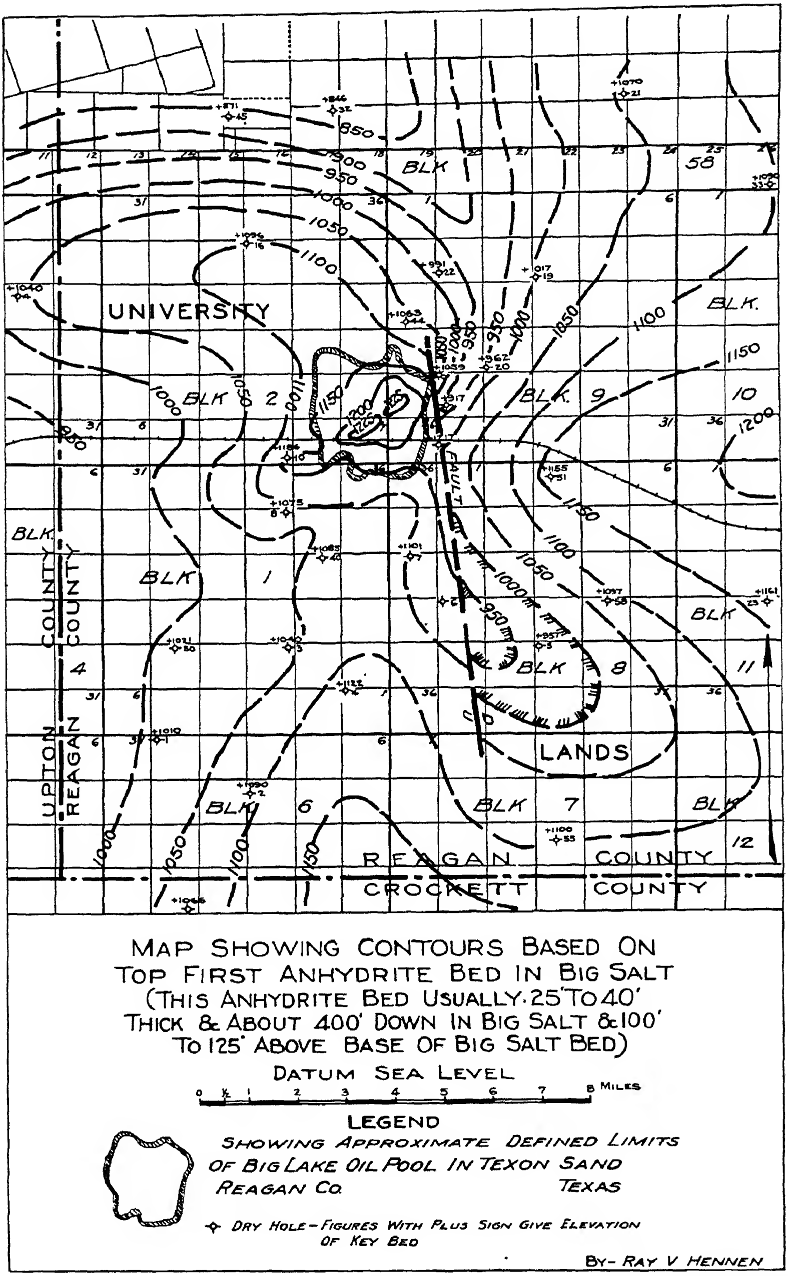


FIG. 4.—Subsurface structure at Big Lake, contoured on top of first anhydrite bed in big salt.

The contours show a pronounced dome in the Upper salt beds, closely related to the Big Lake pool and exhibiting a closure slightly in excess of 125 feet. It is much more pronounced than the dome in the surface rocks (Fig. 3). The outside boundary of the oil pool, for the Texon zone, corresponds approximately with the 1,150-foot contour. Although the configuration of the dome is affected by the fault, yet it is evident that northwest-southeast elongation prevails for the structure.

Figure 4 also shows a fault that will be discussed on a subsequent page.

Contours on Texon discovery oil zone (Fig. 5).—Figure 5, in addition to exhibiting all producing oil wells in both the Shallow and Texon oil zones for the Big Lake pool, gives contours showing the elevation below sea-level of the latter zone. Within its boundary it also gives the location of all dry holes that have been completed outside the pool. These contours indicate a pronounced doming in the Texon zone of much greater structural amplitude than for the salt beds (Fig. 4). The -400-foot contour is the lowest closure and the -150-foot the highest, thus giving a closure of 250 feet. This closure is double that for the salt beds (Fig. 4) and nine to ten times greater than for surface beds (Fig. 3).

The dome has a marked northwest-southeast elongation, but it also possesses considerable northeast-southwest elongation which may have been caused by the fault on the east side of the pool. The outer boundary of the Big Lake pool, in the Texon zone, corresponds approximately with the -300-foot contour (Fig. 5).

Presence of fault.—A pronounced normal fault, whose position is based entirely on a study of the logs of wells adjacent to it, is shown (Figs. 4 and 5) immediately on the east side of the Big Lake pool, bearing slightly east of south. The downthrow which is on the east side is evidently greatest (250 feet) in the Texon zone, in the southwest part of Sec. 26, Block 9 (Fig. 5). Northward from this point the fault seems to disappear near the center of the east line of Sec. 24, Block 9. Southward, it evidently terminates in the northern edge of Sec. 23, Block 8.

No evidence of this fault was found at the surface, nor has a study of well logs adjacent to it revealed its presence in the Cretaceous. Its formation evidently antedates Comanche time, and it may be older than Triassic. It is believed that its formation is synchronous with that of the Big Lake dome in the Permian strata and that it has contributed largely in accentuating the structural relief of the Texon zone.

Data on the elevation of the top of the Big Lake lime, in the numerous wells that have been drilled in eastern Upton and southern Reagan counties and the adjacent part of northern Crockett County, show a marked

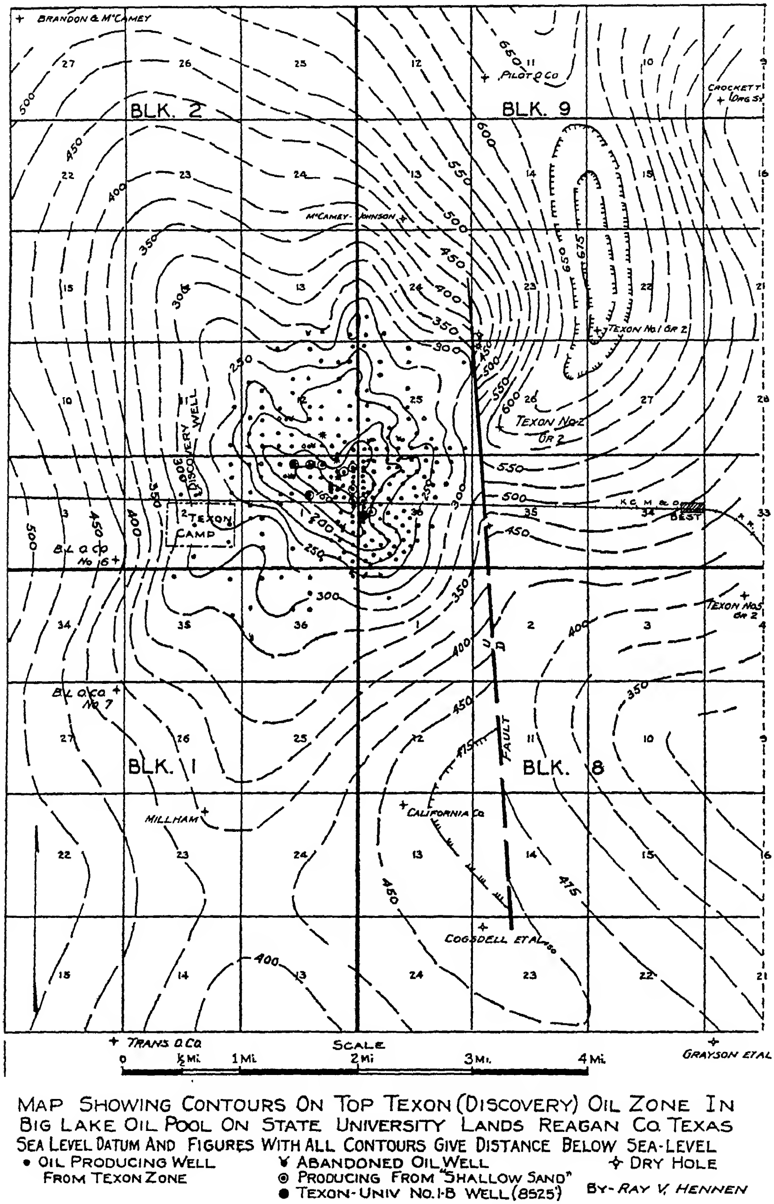


FIG. 5.—Subsurface structure at Big Lake, contoured on top of Texon (discovery) oil zone.

subsurface line of anticlinal folding with an axis plunging northwestward through the Big Lake dome. Within the area embraced by Figure 5, the contours show evidence of this line of folding, both in Blocks 2 and 8. It is very probable that the fault (Figs. 4 and 5), cutting southward across this line of folding, was an important factor in the formation of the Big Lake dome.

OIL-PRODUCING ZONES

Three oil-producing zones have been developed on the Big Lake dome, but only two of them, namely, the Shallow sand and the Texon zone, have yet produced oil in paying quantities. The relative position of these zones in the rock column is shown at the left margin of the cross section (Fig. 2). The possibilities of the third are yet to be determined. These are described in descending order.

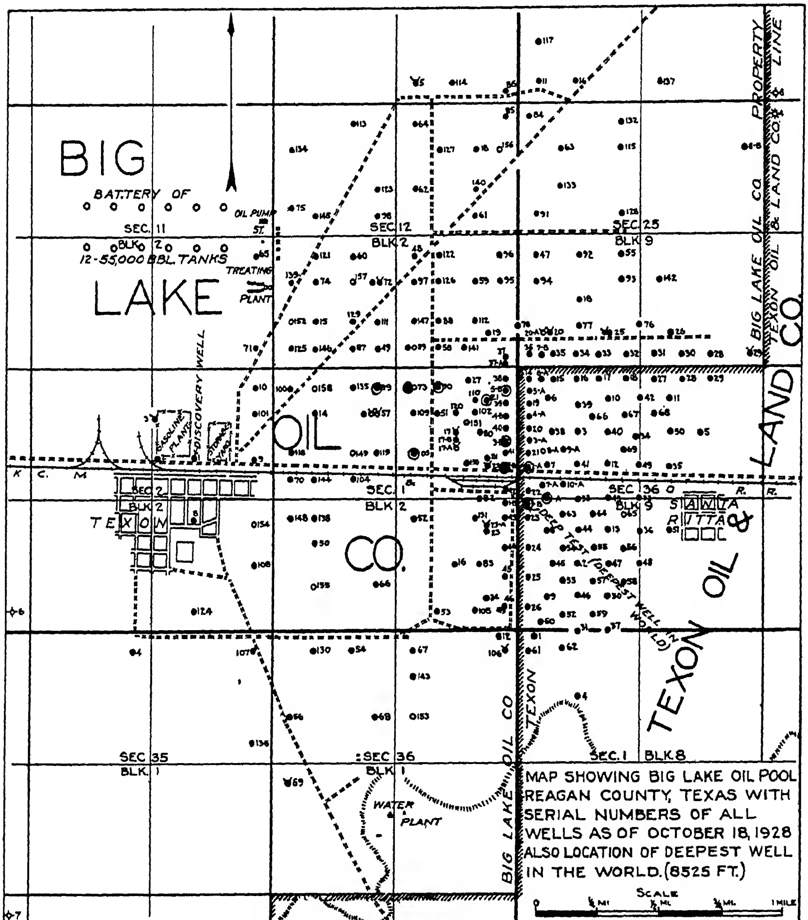
SHALLOW OIL SAND

The Shallow producing zone in the Big Lake pool is generally encountered in wells near the apex of the dome at a depth of approximately 2,450 feet, or approximately 400 feet above the top of the Big Lake lime. This zone is a silty, medium-grained sand, ordinarily reddish brown in color and of non-uniform thickness, ranging from 30 to 50 feet. Both the oil and gas from this horizon are confined to wells near the apex of the dome (see legend, Figs. 5 and 6) or above the −200-foot contour (Fig. 5). Eleven wells have been completed in it as oil producers. The Big Lake Oil Company's University No. 17 (Fig. 6) was the largest "gasser" in the field in this Shallow zone. Its initial volume was more than 87,000,000 cubic feet daily, with a rock pressure of 850 pounds to the square inch.

TEXON OIL ZONE

The Texon oil zone is at a depth ranging from 50 to 100 feet below the top of the Big Lake lime. Its depth from the surface ranges from 2,845 feet, at the Big Lake Oil Company's University No. 51 on the apex of the dome, to 3,137 feet at the same company's University No. 69 in the southern edge of the pool (Figs. 5 and 6). It is the most important oil horizon developed in the Big Lake pool and has produced by far the greatest amount of oil. This zone is an oölitic dolomite, ranging in thickness from 10 to 60 feet, but averaging slightly more than 22 feet, as determined by the average of the first 99 wells completed in the pool by the Big Lake Oil Company. Bottom water occurs 5–10 feet below the oil-producing part, and care must be exercised not to drill too deeply into the formation. Fortunately, a hard ledge intervenes between the oil "pay"

and water, making it possible to "plug back" wells successfully for a short time. Later, water oozes upward to the pay zone and probably accounts for the presence of water in wells in the Texon zone after they have been producing for some time, even at high structural levels.



LEGEND:- ● SHALLOW SAND OIL • TEXON ZONE OIL • DRILLING WELL ¥ ABANDONED WELL.
BY-RAY V. HENNEN

FIG. 6.—Big Lake oil pool development map.

Physical structure.—The following interesting description of the Texon zone, from a microscopic study of its physical structure, has been given by Sellards and Patton.

The oölites in this horizon are very numerous and in some cases make up nearly the entire rock. They vary in size from 0.2 mm. to 0.5 mm., the greater number being near the latter size. They are concentric in structure and usually show a central body or nucleus, often consisting of a sand grain. . . . . In many cases, the oölites break out from the matrix when the rock is broken up by the drill and are found in the samples as separate particles. On the other hand the oölites are in some cases firmly imbedded in the matrix, but the rock is nevertheless quite porous. In cases where oölites break out easily from the matrix they might be mistaken for coarse sand by a casual observer, and in one case at least they were so recorded by the driller. This may partly account for the persistence with which the drillers insist that the production comes from a sand. Micro-chemical tests show that, aside from the occasional sand grain nucleus in the oölites, the rocks vary from relatively pure limestone to pure dolomite. This oölitic zone is not only a distinctive but a very constant zone and there is practically no instance of a well within the field, of which a complete and carefully kept set of samples is available, in which this zone is not easily and definitely identified.[1]

Continuity and porosity.—The Texon oil zone, although not uniform in thickness, is persistent throughout the field; and thus far no dry holes have been completed in it within the limits of the pool.

This zone evidently possesses a large amount of pore space, but the exact percentage of porosity has not been determined. All the wells that have been completed in the field have penetrated this horizon with standard drilling tools, so that no representative specimen for porosity tests, in the form of cores from the pay zone, has been obtained. The prolific producing character of the wells indicates high porosity.

Source of oil and gas.—There has been much discussion among geologists as to the source of the oil and gas that is being produced from the Permian dolomitic limes of West Texas and southeastern New Mexico. Some maintain that the oil has migrated upward from the dark to black carbonaceous shales of the Pennsylvanian. Others incline to the belief that sufficient minute organic life occurred in the Permian seas of West Texas to act as source material for oil and gas during that time when an inland Permian sea was still connected southwestward with the ocean; further, that when this southwestern outlet was cut off, resulting in a closed inland Permian sea, or lake, the pickling character of the resulting highly saline waters tended to preserve on the sea floor the organic life in a form adaptable to make it act as source material for oil and gas.

Both theories have considerable merit, but the writer is inclined to favor the latter. In other words, it is believed that the source of the oil

[1] E. H. Sellards and Leroy T. Patton, *op. cit.*, pp. 375–76.

in the Texon zone is closely related to the dolomitic lime in which it occurs. It is very significant that in the Permian limes of this character, ranging from 800 to 1,000 feet in thickness, are found all the present prolific oil-producing zones of West Texas and southeastern New Mexico. A further corroboration that the oil is indigenous to these Permian limes is the fact that at their outcrops in West Texas and southeastern New Mexico freshly broken fragments from them have a marked petroleum odor.

THIRD, OR DEEP, OIL ZONE

A Third, or Deep, oil zone has been developed on the Big Lake dome at a depth of 6,284 feet, in Well 18 (Figs. 1, 2, and 6). This is reported by the drillers as a sand 15 feet in thickness. It lies 3,434 feet below the top of the Big Lake lime (Fig. 2). Its relative position in the rock column is exhibited in the log of this deep test (Table II), and the data therewith shows that drilling on it was still progressing at a total depth of 8,407 feet on October 30, 1928. Since an effort is being made to explore the underlying formations as deeply as possible, no attempt has yet been made to tube the well and make it a producer.

The oil from this zone is reported as free of sulphur and with a gasoline content of 35 per cent, and has given a gravity test of 38.7° Bé. The possibilities, from a commercial standpoint, for the Third oil zone on the Big Lake dome are yet to be determined; but, judged by the thickness of "pay" encountered, it is problematical whether wells from it would be a paying proposition if the expense of such deep drilling is considered.

RELATION OF ACCUMULATION TO STRUCTURE

REGIONAL

The Big Lake oil pool is on the southeast structural slope of the Permian basin, just as the Yates pool (Fig. 1) of Pecos County is on the southern slope of the same basin; and the McCamey, Church and Fields, Hendricks, and Artesia pools are on the southwestern and western slopes of this basin. In other words, all the pools mentioned, including the Big Lake pool, are located on the rim of a great structural basin, a feature that is characteristic of some of the great oil pools of the world.

LOCAL

It has long been observed that where oil pools are found on the rims of great structural basins, there is generally some pronounced local structural feature to form the trap necessary for segregation of the oil into a pool, especially in zones carrying water. Figures 4 and 5 show a pro-

nounced dome in the Permian beds, and particularly Figure 5, for the Texon oil zone.

The accumulation of oil in the shallow sand is confined to the apex of the dome, or above the −200-foot contour (Fig. 5) of the Texon sand. Below this last-mentioned structural level, edge water prevails.

In the Texon sand the oil accumulation extends from the apex of the dome down to approximately the −300-foot contour (Fig. 5); in fact, this structural level is considered the approximate outer boundary of the pool, and below it edge water prevails. Just as evidently happens on the Yates dome in Pecos County, Texas, the east half of the Big Lake pool has its richest saturation of oil for the Texon zone.

MIGRATION

A glance at the Big Lake dome, as exhibited in both Figures 4 and 5, shows there must be a large accumulation area associated with the dome for the lateral migration of oil in the Texon zone that is believed to have occurred in the segregation of the pool on the dome at this horizon. As discussed on a preceding page, under the description of the Texon zone, it is not believed that the oil migrated upward from Pennsylvanian beds to the Texon zone.

It has been somewhat of a puzzle to account for the presence of oil and gas in the Shallow sand on this dome. The large volume of gas encountered with the oil "pay" is known as a "sweet gas," being practically free of sulphur and non-poisonous in character. This is in marked contrast to the condition prevailing for the gas associated with the Texon zone oil. It suggests that the oil and gas may have migrated from the Texon oil zone up the plane of the fault on the east flank of the dome (Figs. 4 and 5) to its present horizon. At approximately 175 feet below the top of the Shallow oil zone there is a thick red sand that generally carries large quantities of water. It can readily be conceived that oil and gas, in passing up the fault plane from the pool in the Texon zone to the horizon of the Shallow sand, would probably have to pass through a considerable volume of water, thus losing by absorption some of their content of hydrogen sulphide.

OIL

AREA OF POOL

Shallow sand.—The limits of the oil pool in the Shallow sand have not been determined because of lack of data in early wells that had the Texon zone as their objective. The pool is evidently confined to the apex of the

dome, with its outer boundary at approximately the level of the −175-foot contour (Fig. 5). Such a limitation gives an area of 275 acres.

Texon zone.—The outer boundary of the oil pool in the Texon zone corresponds approximately with the −300-foot contour (Fig. 5). A careful planimetric determination of its area on a map from which Figure 5 has been reduced gives 3,500 acres for the total area of the pool in the Texon zone.

PHYSICAL AND CHEMICAL CHARACTER OF OIL

Texon zone.—Both the physical and chemical character of the oil from the Texon zone, at Big Lake dome, have been determined by the United States Bureau of Mines.[1] The results of this investigation are given in Table IV. Table V gives data indicating the base of the oil from the Texon zone and a comparison of it with oil from other well-known West Texas pools.

Shallow sand zone.—No such complete analysis of the physical and chemical character of the oil from this sand has been available, as for the oil from the Texon zone. The following approximate analysis of crude oil from it, at the Big Lake pool, is furnished on the authority of E. C. Stearns, general manager of the Big Lake Oil Company:

Gravity	36.9° Bé.
Gasoline, per cent	32.5
Kerosene, per cent	12.5
Bottoms, per cent	55.0

The oil is very similar to that from the Texon zone and is believed by Stearns to have a slightly less sulphur content.

PRODUCTION DATA

The initial daily potential production of wells from the Texon zone in the early stages of the pool's development ranged from 150 barrels at the discovery well to 4,200 and 8,750 barrels at the Big Lake Oil Company's University No. 11 and No. 18, respectively (Fig. 6). University No. 1 well of the Texon Oil and Land Company had an initial daily production of 5,000 barrels. An average initial daily potential production of 99 consecutive wells of one of the companies was 1,180 barrels per well.

The oil-production data (Table VI) on the Big Lake pool are given on

[1] "Analyses of Crude Oil from the West Texas District," *Report of Investigations, Serial No. 2849* (December, 1927), pp. 6, 7.

TABLE IV

SAMPLE NO. 27866, TEXAS, BIG LAKE FIELD, REAGAN COUNTY, SAND-PERMIAN LIME, COMPOSITE SAMPLE, DEPTH 2,900–3,100 FEET

Specific gravity..................0.834
Saybolt Universal viscosity at 70° F........................47 sec.
Saybolt Universal viscosity at 100° F........................41 sec.

A.P.I. gravity..................38.2°
Percentage of sulphur..........0.36
Percentage of water..............Nil
Pour point.............below 5° F.
Color.......................green

DISTILLATION, BUREAU OF MINES—HEMPEL METHOD

Temperature Degrees C.	Percentage Cut	Sum per Cent	Specific Gravity Cut	Degrees A.P.I. Cut	Viscosity at 100° F.	Cloud Test Degrees F.	Temperature Degrees F.
Air Distillation. Barometer, 746 Mm. First Drop, 29° C. (84° F.)							
Up to 50	2.1	2.1	0.668	80.3	......	......	Up to 122
50–75	2.3	4.4					122–67
75–100	5.5	9.9	0.705	69.2	......	......	167–212
100–125	7.4	17.3	0.738	60.2	......	......	212–57
125–50	6.3	23.6	0.758	55.2	......	......	257–302
150–75	4.5	28.1	0.779	50.1	......	......	302–47
175–200	4.7	32.8	0.795	46.5	......	......	347–92
200–25	4.5	37.3	0.811	43.0	......	......	392–437
225–50	5.3	42.6	0.825	40.0	......	......	437–82
250–75	5.0	47.6	0.835	38.0	......	......	482–527
Vacuum Distillation at 40 Mm.							
Up to 200	5.1	5.1	0.855	34.0	41	5	Up to 392
200–25	5.8	10.9	0.861	32.8	48	30	392–437
225–50	5.1	16.0	0.870	31.1	66	50	437–82
250–75	4.1	20.1	0.886	28.2	105	70	482–527
275–300	6.1	26.2	0.897	26.3	200	90	527–72

Residuum................24.9 per cent
Carbon residue of residuum. 4.6 per cent
Distillation loss............1.3 per cent
Carbon residue of crude.....1.1 per cent

APPROXIMATE SUMMARY

	Percentage	Specific Gravity	Degrees A.P.I.	Viscosity
Light gasoline	9.9	0.689	73.9	....
Total gasoline and naphtha	32.8	0.741	59.5	....
Kerosene distillate	9.8	0.819	41.3	....
Gas oil	13.7	0.849	35.2	....
Non-viscous lubricating distillate	8.8	0.862–0.884	32.7–28.6	50–100
Medium lubricating distillate	5.7	0.884–0.897	28.6–26.3	100–200
Viscous lubricating distillate	3.0	0.897–0.904	26.3–25.0	Above 200
Residuum	24.9	0.940	19.0	....
Distillation loss	1.3	....	....	....

TABLE V

DATA INDICATING THE BASE OF THE CRUDE OIL

Sample No.	Field	Sand	Depth in Feet	Fraction Distilling at Atmospheric Pressure 250°–275° C. (482°–527° F.)		Fraction Distilling at 40 Mm. Vacuum 250°–300° C. (527°–572° F.)	Base of Crude
				Specific Gravity	Degrees A.P.I.	Cloud Point, Degrees F.	
27866.....	*Big Lake*	Permian lime	2,900–3,100	0.835	38.0	90	Intermediate
27856.....	Chalk	Chalk	1,770–1,800	0.837	37.6	90	Intermediate
27858.....	Chalk	Chalk	1,600–1,630	0.836	37.8	90	Intermediate
27857.....	Chalk	Porous limestone	2,956–2,990	0.851	34.8	95	Intermediate
27860.....	Church and Fields	Permian lime	2,900–3,200	0.840	37.0	90	Intermediate
27861.....	McElroy	Permian lime	2,800–2,900	0.841	36.8	85	Intermediate
27862.....	McElroy	Permian lime	2,800–2,900	0.841	36.8	90	Intermediate
27863.....	McCamey	Permian lime	1,800–2,300	0.858	33.4	50	Intermediate
27864.....	McCamey	Permian lime	1,800–2,300	0.853	34.4	55	Intermediate
27867.....	World	Permian lime	2,500–2,700	0.844	36.2	80	Intermediate
27859.....	Hendricks	Permian lime	2,700–3,100	0.857	33.6	*	Naphthene
27865.....	Yates	Permian lime	1,000–1,500	0.854	34.2	*	Naphthene

* Below 5° F.

the authority of E. C. Stearns, general manager, Big Lake Oil Company, as of October 1, 1928.

An analysis of the production figures, as of October 1, 1928, reveals that the total gross production from the Texon zone is 97.16 per cent of

TABLE VI

OIL PRODUCTION, BIG LAKE POOL

Gross Daily from Texon Zone Barrels	Gross Daily from Shallow Sand Barrels	Gross Daily for Field Barrels
17,483	839	18,322
Total Gross from Texon Zone Barrels	Total Gross from Shallow Sand Barrels	Total Gross for Field Barrels
35,210,344	1,028,107	36,238,451
Number Wells from Texon Zone	Number Wells from Shallow Sand	Total Wells for Field
216	9	225

the total gross from both zones, and that for the Shallow sand, 2.84 per cent. The 460 acres of the Texon Oil and Land Company, fully developed for the Texon zone, had already produced from this horizon, 25,700 barrels of oil to the acre and on that date was adding to its recovery at an annual rate of 3,100 barrels to the acre. These results justify an estimate that the ultimate recovery from this 460-acre unit may be 35,000 barrels to the acre from the Texon zone, which has an average thickness of less than 25 feet.

GAS

SHALLOW SAND

The Shallow oil sand of the Big Lake dome has been a prolific gas producer in several wells near the apex of the structure, or above the −200-foot contour (Fig. 5). One well (Big Lake Oil Company's University No. 17) had an initial volume of slightly more than 87,000,000 cubic feet daily, with a rock pressure of 850 pounds to the square inch. This well furnished fuel for field operations for a considerable time. Other notable gassers in this horizon are the Big Lake Oil Company's No. 21 and No. 102, which are still furnishing fuel from this horizon for the camp at Texon.

The gas from the shallow sand is known locally as "sweet gas" in that it is non-poisonous in character. Tests show that it contains less than 0.01 per cent of hydrogen sulphide.

TEXON ZONE

The Texon zone produces a considerable amount of gas with the oil. A very few of the wells, when first opened, produced approximately 1,000,000 cubic feet of gas daily with their oil. During the first three years after the field was opened, this gas was present in sufficient volume and pressure to cause the wells to flow their production. At the present time all producing wells in the field are pumped.

The gas from the Texon zone is now collected by a system of gathering lines from the producing wells to a casing-head plant in the field that uses about 3,500,000 cubic feet daily. After it passes through the plant, the residue is treated and then used to supplement the Shallow sand wells in supplying the fuel for the camp.

The gas from the Texon zone is poisonous in character, so that considerable care has to be exercised when wells are being completed in the "pay." The United States Bureau of Mines has investigated the character of this gas and the following is taken from their report.

> The 'poison gas' is present with the oil but fortunately not in large quantities. If the same volume were present as in the Panhandle field, the effect would be disastrous. Analyses of eight samples of the poison gas collected from eight different wells, oil separators, or flow tanks into which the wells were producing, show amounts of hydrogen sulphide ranging from 8.1 to 10.5 per cent. The concentration appears to vary with the location of the wells. Those wells in the extreme east of the field produce the larger amount, and those in the southwest the lesser.[1]

PRESENCE OF WATER

Edge water is present in the Shallow sand of the Big Lake pool, generally below the −200-foot contour level (Fig. 5).

In the Texon zone, edge water, sulphurous in character, prevails in the oil pay part of the zone at approximately the position of the −300-foot contour (Fig. 5). Five to 10 feet below the oil pay part of the Texon zone, bottom water, sulphurous in character, prevails even at high structural levels. As mentioned under the description of the Texon zone, this bottom water can be successfully plugged off because of a hard ledge, 5–10 feet in thickness, intervening between the oil "pay" and water. This bottom water is evidently diminishing in volume and pressure. Formerly when wells were drilled into it, this water would rise almost 2,200 feet in the hole. New wells recently drilled into it show that it now rises only 1,200 feet in the hole, and the water carries less sulphur than formerly.

[1] "Hydrogen Sulphide Poison in the Texas Panhandle, Big Lake, Texas and McCamey, Texas," *Report of Investigations, Serial No. 2776* (October, 1926), p. 7.

It is evident that this bottom water, even on the apex of the dome, oozes up slowly through the intervening ledge into the oil "pay," as all wells in the field pump some water with their oil. The minimum amount of this water is 5 per cent of the total fluid. The water is easily separated from the oil and does not seem to interfere seriously with the oil production. In fact, it seems to prevent paraffining of the pay zone, thus permitting the oil to flow more freely into the well.

DRILLING AND PRODUCTION METHODS

All the wells in the Big Lake pool, with one exception, have been drilled with standard cable tools, using standard 81-foot steel derricks. A few wooden rigs were used at the start. Rotary drilling equipment was tried on one well down to the top of the Big Lake lime, but the hard anhydrite beds encountered made this method unsatisfactory.

At first, all the wells of the Big Lake Oil Company were pumped with individual gas engines, but in July, 1927, a change was made to individual electric motors, which resulted in great economy of operation. Six to eight months later, the Texon Oil and Land Company also changed from individual gas engines to individual electric motors for all their wells except ten, which are pumped from a central power driven by an electric motor. Electric current for this purpose is furnished the field by the Pecos Valley Power and Light Company from its power plant at Girvin, Texas.

FUTURE DEVELOPMENT

SHALLOW SAND

It is probable that the Shallow sand may produce much more oil in the future from wells drilled to it for that purpose, especially near the apex of the dome. Because of the large volume of gas with high rock pressure encountered in it, many wells were loaded with mud and water until that stratum was drilled through. This was to prevent probable loss of a well to the Texon zone through escape of uncontrollable amounts of gas, with the latter zone at that time being the main objective. This loss happened in two or three wells.

TEXON ZONE

When, early in 1927, the price of this crude oil was cut approximately $1.00 per barrel, drilling operations were immediately curtailed, leaving an area of approximately 3,050 acres within the limits of the pool for the Texon zone, with only 147 wells. On the basis of 1 well to each 10 acres, it is evident that many proved locations are yet to be drilled.

THIRD, OR DEEP, SAND

As mentioned on a preceding page, under a description of the Third, or Deep, sand, it is problematical whether the amount of production that may be obtained from this deep sand will warrant the large cost of drilling operations. More will be known about the future development of this horizon when the deep test (Well 18, Figs. 1 and 2) is plugged back to it, the well tubed, and its oil-producing capabilities determined.

APPENDIX[1]

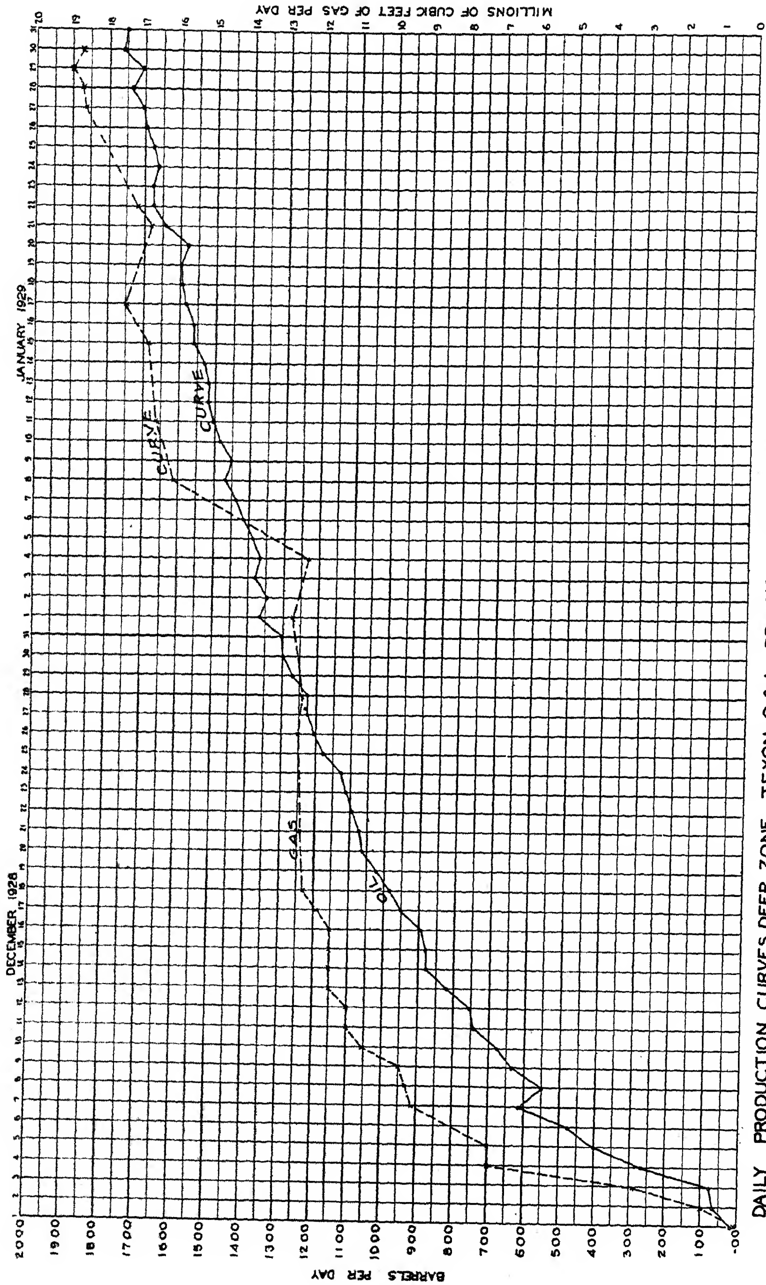
INTRODUCTION

The original manuscript for this paper was completed on November 11, 1928. At that time the Texon Oil and Land Company's University No. 1-B well (Well 18 of Fig. 2) was drilling at a depth of 8,407 feet. Later, by December 1, it had penetrated more than 100 feet deeper and had developed another remarkable oil- and gas-producing horizon at 8,520–25 feet, that has herein been designated the "Fourth" oil zone. Because of the large volume of gas with high rock pressure (probably 3,000 pounds to the square inch) encountered with the oil in so small a hole ($5\frac{3}{16}$ inch), it was found impossible to lower the drilling tools to drill deeper into the pay zone. In spite of this, however, the well has been slowly drilling itself in below its total drilled depth of 8,525 feet, during the months of December and January. During this period its oil production has increased at an average daily rate of 28.4 barrels, with a marked increase in its daily volume of gas on open-flow tests, and for the month of December flowed a total gross of 25,848 barrels of oil, and for January, 48,298, or a total of 74,146 barrels for its first two months. This increase is strikingly exhibited by the curves shown in Figure 7, which are based on the daily gauges at 7:00 A.M. of each date as furnished by the Texon Oil and Land Company (Table VII).

The producing record of this well is remarkable and exceptional; and, so far as known to the writer, no such sustained increase in daily oil production, after drilling had ceased, has ever been associated with any other well in the United States for so long a period. Again, it is not only the deepest oil-producing well in the world but also the deepest boring ever drilled for any purpose. Its complete log, classified tentatively to its present total depth of 8,525 feet, is given on pages 508–11, in the original paper. It is believed that this deep oil zone (Fourth) occurs in pre-Pennsylvanian rocks, a conclusion seemingly corroborated by the analyses of the oil herein.

The University 1-B well was drilled with standard cable tools to its total depth of 8,525 feet, with electricity used as power for drilling operations. This, no doubt, resulted in less cost than if steam had been used, in that much less time was consumed in getting the drilling tools in and out of so deep a hole. This cost has been estimated by its owners to be $140,000.00. On January 31, 1929,

[1] January 31, 1929.



DAILY PRODUCTION CURVES, DEEP ZONE, TEXON O. & L. CO., NO. 1-B. UNIV., DEPTH 8525' REAGAN COUNTY, TEXAS.

FIG. 7

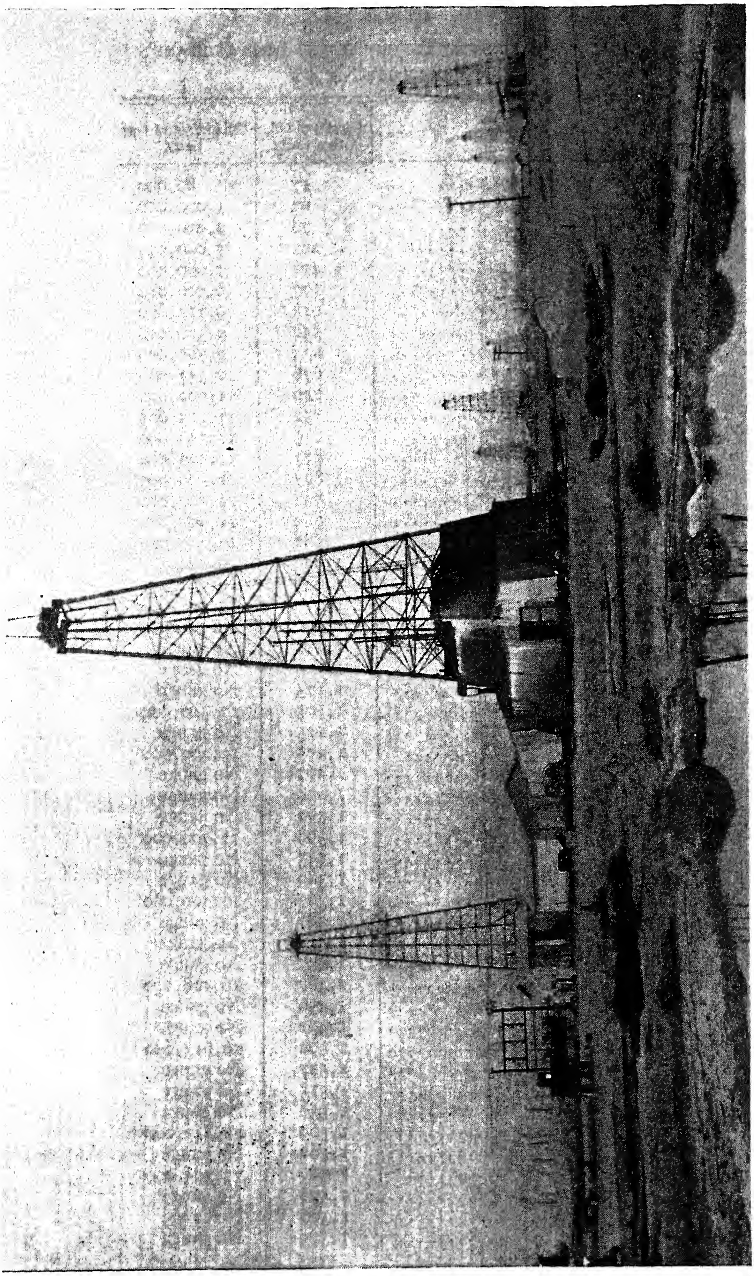


FIG. 8.—Photograph of Big Lake pool, showing in foreground deepest (8,525 feet) oil producer and deepest well ever drilled for any purpose (No. 18 of Figure 2 and Table III).

TABLE VII

DAILY PRODUCTION, TEXON OIL AND LAND COMPANY'S UNIVERSITY NO. 1-B

Date		Barrels of Oil, Gross Daily	Cubic Feet of Gas Daily
1928, December	1	17	86,000
	2	66	1,000,000
	3	78	2,900,000
	4	265	7,000,000
	5	402	7,000,000
	6	477	8,000,000
	7	615	9,114,000
	8	552	9,300,000
	9	635	9,500,000
	10	676	10,547,000
	11	740	11,000,000
	12	752	11,000,000
	13	819	11,500,000
	14	877	11,500,000
	15	877	11,500,000
	16	892	11,500,000
	17	952	11,900,000
	18	982	12,300,000
	19	1,020	No gauge
	20	1,060	No gauge
	21	1,070	12,400,000
	22	1,090	No gauge
	23	1,112	No gauge
	24	1,125	No gauge
	25	1,175	No gauge
	26	1,205	12,500,000
	27	1,225	No gauge
	28	1,225	12,400,000
	29	1,267	No gauge
	30	1,298	No gauge
	31	1,302	No gauge
1929, January	1	1,368	12,700,000
	2	1,345	No gauge
	3	1,380	No gauge
	4	1,367	12,300,000
	5	1,387	No gauge
	6	1,417	No gauge
	7	1,437	No gauge
	8	1,467	16,108,000
	9	1,450	No gauge
	10	1,482	No gauge
	11	1,502	16,613,000
	12	1,517	No gauge
	13	1,515	No gauge
	14	1,530	No gauge
	15	1,560	16,842,000
	16	1,560	No gauge
	17	1,582	17,505,000
	18	1,590	No gauge
	19	1,596	No gauge
	20	1,575	No gauge

TABLE VII—*Continued*

Date	Barrels of Oil, Gross Daily	Cubic Feet of Gas Daily
1929, January 21	1,640	16,800,000
22	1,675	17,169,000
23	1,675	No gauge
24	1,662	No gauge
25	1,677	No gauge
26	1,692	No gauge
27	1,705	18,654,000
28	1,735	18,755,000
29	1,705	19,085,000
30	1,755	18,755,000
31	1,750	No gauge

74,146 barrels of oil had been produced, of which total probably not more than 3,000 barrels, or 50 barrels daily, has come from the Third zone at 6,284 feet, occurring 100 feet below the bottom of the last string of casing. It is probable that before the expiration of another forty days the entire cost of the well will be refunded to its owners. If it had been possible to drill deeper into the pay zone, there can hardly be any doubt but that a much larger well would have resulted.[1]

The importance of this deep oil zone (Fourth) to the Permian basin region of West Texas and southeastern New Mexico, from an oil reserve standpoint, can scarcely be overestimated. It has demonstrated that the beds of the Pennsylvanian may offer possibilities for large oil production on many of the structures associated with the oil pools of the Permian in this region (Fig. 1). It is believed for this reason that the officials of the Texon Oil and Land Company are deserving of the highest praise for their courage and persistence in sinking the well to so great a depth to determine the oil possibilities of these older rocks.

[1] Subsequent note, July, 1929. Monthly gross production from the deep "pay" since completion of this well on December 1, 1928, has been added in the following table. On July 5, 1929, it attained its greatest single day's production (2,677 barrels) together with 25,177,000 cubic feet of gas:

	Barrels Oil
December, 1928	25,299
January, 1929	48,697
February 1929	53,551
March, 1929	67,052
April, 1929	70,222
May, 1929	78,617
June, 1929	78,331
Total gross	421,769

OIL FROM FOURTH ZONE

Area of pool.—The area of the oil pool on the Big Lake dome, that has been opened from the Fourth zone, cannot be determined at this stage of its development. Although the well is not on the apex of the dome, as determined for the Texon zone (Fig. 5), it occurs at a high structural level on the dome; and it is believed that this deep zone will produce at much lower structural levels in other wells a considerable distance from the University 1-B well and that the pool in it may cover practically the same area (3,500 acres) as that for the Texon sand.

Physical and chemical character of oil.—Very complete tests of the oil from this Fourth zone, in the University 1-B well, have been made recently at the Fort Worth Refinery of the Transcontinental Oil Company. Concerning these tests, A. J. Slagter, general superintendent of refineries, gives the following statement.

From the results obtained on both the experimental and the commercial run on Texon crude oil, made at our Fort Worth, Texas, refinery, we find that all of the characteristics of this crude correspond almost identically with the light Pennsylvania crudes, namely, that it is low in sulphur (0.19 per cent), that the specific gravity and boiling-points of the various fractions correspond with the Pennsylvania crudes, that it is a strictly paraffin base crude containing 0.35 per cent of paraffin wax and 5 per cent of lubricating oils corresponding in every respect with Pennsylvania lubricating oils, and that it is practically free from any asphaltic pitch.

The following "Report No. 1" (Table VIII) shows the Engler distillation made on each 5 per cent cut to 95 per cent of the crude, together with Engler distillation of the Texon crude itself.

The attached "Report No. 2" (Table IX) gives a summary of the characteristics and percentages of overhead products and residuals run to different percentages.

The attached "Report No. 3" (Table X) shows the results from the commercial run of 500 barrels made at the Fort Worth refinery, said run being made to a 7 per cent residual.

TABLE VIII

REPORT NO. 1—SPECIAL LABORATORY REPORT OF THE TRANSCONTINENTAL OIL CO., FORT WORTH REFINERY PLANT, JANUARY 18, 1929

ENGLER DISTILLATIONS MADE ON EACH 5 PER CENT CUT OF TEXON CRUDE*

(FOURTH ZONE)

Percentage	Temperature Degrees F.	Specific Gravity	I.B.P.	Temperature at Following per Cent Off									Maximum Boiling Point	Color	Percentage of Recovery
				10	20	30	40	50	60	70	80	90			
5.....	90 156	85.0	76	91	104	115	127	142	159	180	213	....	313	25 plus	88.0
10.....	175	82.1	80	96	107	120	133	145	160	180	205	....	313	25 plus	91.0
15.....	192	77.0	88	112	123	134	145	156	169	184	203	228	313	25 plus	97.0
20.....	208	72.4	108	134	144	154	164	174	185	196	212	240	316	25 plus	98.5
25.....	225	68.4	126	156	164	174	184	192	203	208	229	258	337	25 plus	99.0
30.....	240	65.0	148	174	184	192	199	207	214	227	245	275	353	25 plus	99.0
35.....	257	61.9	167	190	201	207	215	224	234	246	263	397	376	25 plus	99.0
40.....	276	59.4	188	211	216	224	232	240	250	262	280	310	393	25 plus	99.0
45.....	294	57.3	204	229	235	242	250	256	268	282	302	336	416	25 plus	99.0
50.....	316	55.3	226	248	254	261	270	278	289	302	316	354	439	25 plus	99.0
55.....	342	53.0	250	273	280	287	294	304	314	327	347	384	465	25 plus	99.5
60.....	370	51.0	282	300	308	315	323	331	341	356	378	416	492	25 plus	99.5
65.....	404	49.0	310	326	334	340	350	361	373	388	410	448	520	25 plus	99.5
70.....	441	46.9	340	358	369	378	388	398	410	427	449	488	555	25 plus	99.5
75.....	480	44.5	380	403	412	426	435	446	458	474	498	537	602	25 plus	99.5
80.....	525	42.2	422	447	455	467	476	487	499	515	535	572	639	25	99.5
85.....	575	40.1	468	492	503	512	522	532	546	561	584	624	680	1½	99.5
90.....	645	37.7	519	551	565	575	586	598	612	630	650	690	742	1½	99.5
95†....	694	35.3	220	578	620	640	653	669	684	700	720	751	760 plus at 92 per cent off		

* Engler distillation of Texon crude: 55.7, 100, 170, 204, 236, 270, 310, 363, 435, 526, 690, and 737.

† Low initial of this cut indicates cracking.

TABLE IX

REPORT NO. 2—SPECIAL LABORATORY REPORT OF THE TRANSCONTINENTAL OIL CO., FORT WORTH REFINERY PLANT, JANUARY 15, 1929

SUMMARY

CHARACTERISTICS AND PERCENTAGES OF OVERHEAD PRODUCTS

Run No.	Viscosity	Specific Gravity	I.B.P.	Temperature at Following per Cent Off									Maximum Boiling Point	Corr.	Dr.	Color	Percentage of Charge	Percentage of Loss	Percentage of Sulphur
				10	20	30	40	50	60	70	80	90							
Residual Gasoline																			
1	70	63.4	104	156	181	200	219	237	258	279	307	345	421	Corr.	Sour	25	63.7	2.1	0.075
2	100	63.4	106	154	180	200	217	237	257	278	305	342	426	Corr.	Sour	25	64.0	1.9	0.075
3	120	63.6	105	156	180	200	218	236	257	278	307	344	425	Corr.	Sour	25	64.3	1.4	0.075
4	140	63.5	107	157	180	201	218	238	257	279	306	344	425	Corr.	Sour	25	64.2	1.7	0.075
Residual Kerosene																			
1	70	43.9	378	408	424	437	450	464	480	499	525	565	624	Corr.	Sour	15–2 D	19.2	....	0.053
2	100	43.0	385	418	436	452	469	486	507	531	558	603	675	Corr.	Sour	10–2 D	24.4	....	0.051
3	120	42.4	385	419	440	456	474	494	516	541	571	620	688	Corr.	Sour	13–2 D	26.2	....	0.077
4	140	42.2	388	423	442	458	478	498	521	548	579	634	697	Corr.	Sour	12–2 D	27.1	....	0.082

CHARACTERISTICS AND PERCENTAGES OF RESIDUALS

(All Viscosities Made at 100°)

Run No.	Viscosity	Gravity	Flash	Fire	Cold	Viscosity	Color	Percentage of Charge	Percentage of Loss	Percentage of Sulphur
1	70	34.1	300	345	70	70	5–D	15.0	....	0.203
2	100	32.6	330	370	75	100	7	9.7	....	0.209
3	120	31.7	355	400	80	119	7	8.1	....	0.218
4	140	30.4	365	415	85	139	7–D	7.0	....	0.324

Sulphur content of crude (percent)..0.190

TABLE X

REPORT NO. 3—COMMERCIAL RUN ON 500 BARRELS, FOURTH ZONE CRUDE TO 7 PER CENT RESIDUAL

Products	Per Cent	Specific Gravity	I.B.P.	M.B.P.	Flash	Fire	Viscosity	Melting-Point	Percentage of Sulphur	Color
Gasoline	66.00	63.5	104	425	.....	.....	.....	......	0.075	25
Kerosene	20.00	43.5	.....	.....	180	.....	.....	......	......	.....
Gas oil	5.65	38.0	.....	.....	.....	.....	.....	......	......	.....
Lube oil*	4.50	29.5	.....	.....	470	520	350	......	......	6–7
Wax	0.35	.....	.....	.....	.....	.....	.....	124–26	......	.....
Loss	3.50	.....	.....	.....	.....	.....	.....	......	......	.....

* The tests and percentage of lube oil were determined in the laboratory from residuum off the refinery run.

ACKNOWLEDGMENTS

In the preparation of this paper the writers have drawn freely on previously published data by the United States Geological Survey and the Bureau of Economic Geology of the University of Texas. They are particularly indebted to the following men who have kindly furnished suggestions and valuable data: Sidney Powers, Amerada Petroleum Corporation; J. A. Udden, Bureau of Economic Geology, University of Texas; J. V. Howell, of Ponca City, Oklahoma; and Virgil Pettigrew, Humble Oil and Refining Company.

LOCATION

The Petrolia oil and gas field is in the northern part of Clay County, Texas, approximately 16 miles northeast of the city of Wichita Falls and 11 miles north of the town of Henrietta. It lies almost entirely in the Parker County School Land Survey, occupying practically all of the northwestern part of this tract. On the north side of the field is the village of Petrolia, from which the field derives its name. This territory is served by the Wichita Valley Railroad, which connects Petrolia with Wichita Falls.

HISTORY

On account of the scarcity of water for drinking purposes, a well was bored in the year 1902 by a Mr. Lochridge, who was seeking to relieve the water situation on his farm in Clay County. At a depth of approximately 150 feet the drill encountered a sand that showed only oil, thus dampening the prospects for a water well. Oil had previously troubled some of the farmers of that district by seeping into their wells, but this was the first occurrence of a stratum producing oil and no water. Although no drilling for oil was done at that time, the Lochridge discovery was the real beginning of the oil industry in this area. Within the brief period of a few years, however, there were several hundred shallow wells producing oil at depths ranging from 150 feet to approximately 720 feet. The entire shallow producing area covered something like 700 acres, which is the crest of the Petrolia structure as it is known today. This was the beginning of what was first called the "Henrietta" oil field, but, as the town of Petrolia soon made its appearance on the north side of the field, the name was changed to the "Petrolia" field. During the early days the acreage was divided into small tracts and townsites; and, as many of these have changed ownership a number of times, there has probably never been a more confused condition of ownership, well locations and numbers than has existed here.

Deeper drilling, and consequently the development of gas, did not begin in the Petrolia field until 1907, when the first gas of importance was found. This discovery led to much greater activity, and within two years there was so much gas that a market was demanded. In answer to this demand the Lone Star Gas Company was organized, which company built a line to Fort Worth and Dallas, a distance of approximately 140 miles. For several years Petrolia was the only gas-producing field of importance in this part of the country, being the sole source of gas for the previously mentioned cities. It is a remarkable fact that a small amount of gas from this field is still being supplied to these cities, although a period of more than 20 years has elapsed since its inception as a gas-producing area.

TOPOGRAPHY

The Petrolia field is on a topographical divide which is drained on the north by Big Wichita River and on the south by Little Wichita River and their tributaries. These streams ultimately empty into Red River. Long Creek, a tributary of Little Wichita River, has entrenched itself through the heart of the field but, being in an immature stage, has not developed any flood plains. The topography has the aspect of a rolling prairie, and the paucity of vegetation gives it an appearance similar to that of the plains country. Elevations in and around the field range from approximately 900 feet to 1,010 feet, the highest point in the county being slightly north of the edge of the field. The elevation at Petrolia station is 993 feet.

SURFACE STRATIGRAPHY

All beds exposed in the Petrolia field and its immediate environs are a part of the Wichita formation of the Permian series, more commonly known as Red-beds. The Permian in north Texas has been divided into three divisions, in ascending order—Wichita, Clear Fork, and Double Mountain—but only the Wichita is found in the area under discussion. Exposures around Petrolia consist chiefly of cross-bedded sandstones, red shales, and a few blue and gray shales. Although thin beds of limestone and gypsum have been reported in some wells in the Wichita formation, it is doubtful if these reports are correct. The shales are of a lenticular nature, and the sandstones are rather discontinuous. This not only is true on the surface but it is verified by well records, certain beds being found in one well that do not seem to be present even in the nearest offset. Very few fossils are found in this formation; most of them are restricted to

plant remains; but a few pieces of carbonized wood or part of a tree trunk have been seen in well cuttings.

SUBSURFACE STRATIGRAPHY

There are no exposures of any of the rocks below the Wichita formation in the area of Petrolia. For this reason a discussion of the underlying beds and their relation to surface beds must be based on conclusions drawn from exposures in other places and from records of deep wells. The lower part of the Wichita and the top of the Cisco, the next lower formation, bear such a marked resemblance to each other that it is almost impossible to designate an exact line of contact between the two. As early as 1891, C. A. White[1] described this condition as follows.

> The Texas Permian, while not contrasting strongly with the Coal Measure formation which underlies it, is readily distinguishable from it by general aspect and lithological character; and yet the Permian strata blend so gradually with those of the underlying Coal Measures . . . . that it is difficult to designate a plane of demarkation in either case.

Because of the scarcity of fossils and failure to preserve well cuttings, we do not know much more of this contact even today, but it is generally conceded that the thickness of the Wichita is approximately 1,000 feet in the vicinity of Petrolia. Udden and Phillips[2] also state that this line of demarkation is uncertain.

We know that the upper 300 feet or more at Electra belong to the Wichita formation and that the shales and sands penetrated from 1,400 to 2,000 feet under the surface belong to the Cisco, but how much of the intervening 1,200 feet should be alloted to each we can only guess from the lithologic appearance of the section as made known by the drillers' records.

As the conditions of deposition of the Upper Pennsylvanian and the basal Red-beds were very similar, causing the two formations to grade very gently into each other, it is easily understood why one finds it difficult to name any certain depth as the contact between them.

Gordon's[3] brief description of the Pennsylvanian rocks of north-central Texas and approximate thicknesses is as follows.

[1] C. A. White, "The Texas Permian and Its Mesozoic Types of Fossils," *U. S. Geol. Survey Bull. 77* (1891), p. 11.

[2] J. A. Udden and D. McN. Phillips, "A Reconnaissance Report of the Geology of the Oil and Gas Fields of Wichita and Clay Counties, Texas," *Univ. of Texas Bull. 246* (1912), p. 86.

[3] C. H. Gordon, "Geology and Underground Waters of the Wichita Region, North-Central Texas," *U. S. Geol. Survey Water-Supply Paper 317* (1913), p. 14.

SECTION OF PENNSYLVANIAN FORMATIONS IN THE WICHITA REGION, TEXAS

	Feet
Cisco formation (clay, shale, conglomerate, and sandstone, with some limestone and coal)	800
Canyon formation (alternating beds of limestone and clay, with some sandstone and conglomerate)	800
Strawn formation (alternating beds of sandstone and clay, with some conglomerate and shale; the lower 1,000 feet consists of blue and black clay locally containing beds of limestone, sandstone, or sandy shale, and a coal seam at the top)	1,900
Total	3,500

Wells located on the top of the Petrolia structure find the Cisco with a thickness ranging from approximately 750 to 850 feet and then pass into thick bodies of limestone, known locally as the "Big lime." Immediately before this limestone is penetrated, the "big gas sands" of the field are found at depths ranging from 1,500 to 1,750 feet. The lower part of this "Big lime" is of Ordovician age (Fig. 1): "The producing sands in Petrolia and Burkburnett, but probably not Electra, directly overlie limestone of Ordovician age in the fields, but on the sides of the anticlines a series of water-bearing sands appear which do not extend over the highest parts."[1] From this it is surmised that the Canyon, Strawn, and Bend are all absent on the top of the Petrolia structure, as it is practically certain that the producing sands at Petrolia are a part of the Cisco.[2] Certain facts set forth by Hager[3] and Roundy[4] tend to substantiate this point of view, and, although paleontological evidence is rather scarce, especially at Petrolia, it is now generally conceded that this lime is of Ordovician age. Three key wells, Byers No. 41 on the northeast flank of the structure, Lochridge No. 6 on the crest, and Halsell No. 1, 18 miles southeast of Petrolia, give considerable evidence that the fore-

[1] Sidney Powers, "Reflected Buried Hills and Their Importance in Petroleum Geology," *Econ. Geol.*, Vol. 17 (1922), p. 247. Subsequent note (July, 1929).—In 1929 samples from several wells southwest of Waurika were examined by B. H. Harlton and from meager fossil evidence it is believed that the upper part of the "Big lime" is Pennsylvanian and the lower part Ordovician, separated by a thick erosional zone. See also, Sidney Powers, "Age of Folding of the Oklahoma Mountains," *Bull. Geol. Soc. Amer.*, Vol. 39 (1929).

[2] J. A. Udden and D. McN. Phillips, *op. cit.*

[3] Lee Hager, "Red River Uplift Has Another Angle," *Oil and Gas Journal* (October 17, 1919), pp. 64, 65.

[4] P. V. Roundy, *U. S. Geol. Survey Bull. 726-F* (1922), p. 293.

going conclusions are well taken. In regard to Byers No. 41, Harlton[1] states: "It may be concluded that the contact between the Carboniferous and Ordovician rocks in Byers 41 is at a depth of about 3,540 feet, based on fossil evidence."

Another important fact connected with this well is that it encountered granite from 4,240 to 4,289 feet (the bottom of the hole) and that it is the only well at Petrolia that has been drilled into igneous rock.

Lochridge No. 6, and several other wells on the highest part of the structure, after passing through the lower zone of the "big gas horizon," approximately from 1,700 to 1,750 feet, went directly into the "Big lime"

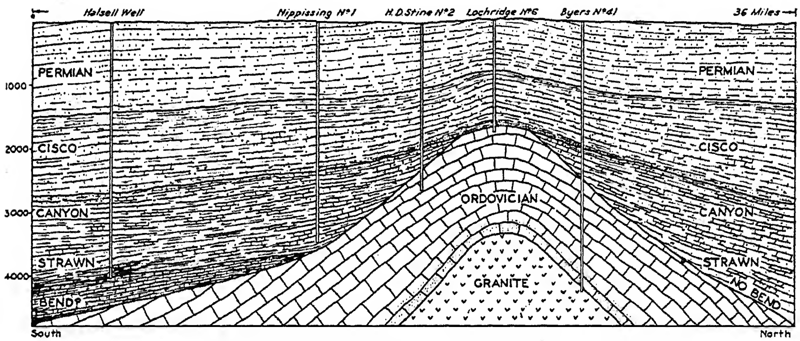


FIG. 1.—Cross section through Petrolia oil and gas field south to Halsell well, Clay County, Texas. Depths in feet. The exact character of contact of Ordovician and granite is unknown.

and stopped after drilling a short distance into it. The Halsell well was drilled to a depth of 3,985 feet without encountering Ordovician rocks, but a significant feature in regard to this well is that the last 15 feet drilled was supposed to be a part of the Bend series.[2] This is the nearest well on the south side of the Petrolia field that has encountered the Bend, and, so far as is known, this formation is not present on the north side of the buried ridge.

The line of contact between the Pennsylvanian and the underlying "Big lime" is unconformable, being very definitely marked in some wells, although in others, such as Byers No. 41, it is somewhat less definite. The fact that more complete cuttings have not been preserved from the

[1] B. H. Harlton, Amarada Petroleum Corporation, Tulsa, Oklahoma, personal communication.

[2] J. A. Udden and D. McN. Phillips, *op. cit.*, p. 81.

deep wells is indeed deplorable; as a result, many geological problems are still unsolved in this part of the country.

SURFACE STRUCTURE

As in most fields where the surface rocks are a part of the Red-beds, plane-table mapping in the vicinity of Petrolia is not very satisfactory. It may be said, however, that the Petrolia dome, or anticline, as revealed on the surface, trends almost north and south and has a closure ranging from approximately 40 to 60 feet. One of the main features of the structure is a pronounced nose on the northeast and a lesser nose on the northwest. By cutting its course through the middle of the field, Long Creek has given it the appearance of a truncated dome; for this reason it is impossible to determine the exact amount of closure.

There are two sandstone beds exposed in this area that have been used in mapping the surface. The higher bed is used as datum, as shown in Figure 2. These beds cannot be followed for any great distance, as they are either eroded or covered by mantle soil. The structure, however, is sufficiently revealed by local dips alone, without correlating the sandstone outcrops; but a combination of the two gives a much clearer idea of its size, shape, and extent. Had these beds been more indurated, they might have formed a rim rock around the structure instead of occurring in isolated patches, as they do, on the flanks of the dome.

In the area near the Petrolia field the dip of the rocks is in complete harmony with the structure, in that they dip away from it in all directions. Consequently, it would be difficult to name any particular direction as regional dip; but outside these environs, where the domes fail to exert their influence, it is the general opinion that a north dip ranging from 30 to 40 feet per mile may be considered as normal. The field is located on a topographic "high," and the reflection of the structure in the topography is a feature worthy of note.

SUBSURFACE STRUCTURE

The Petrolia field is one of several oil and gas fields in north Texas located on a long buried ridge, or chain of hills, that lies along the general course of Red River and is parallel to some extent with the Wichita-Arbuckle uplift in southern Oklahoma. This buried ridge is commonly known as the Red River arch, a zone in which lower Pennsylvanian and Mississippian formations seem to be absent on the high points of the buried hills and in which the Arbuckle or Ellenburger limestone is encountered in wells at depths much less than in the surrounding country.[1]

[1] William Kennedy, private report.

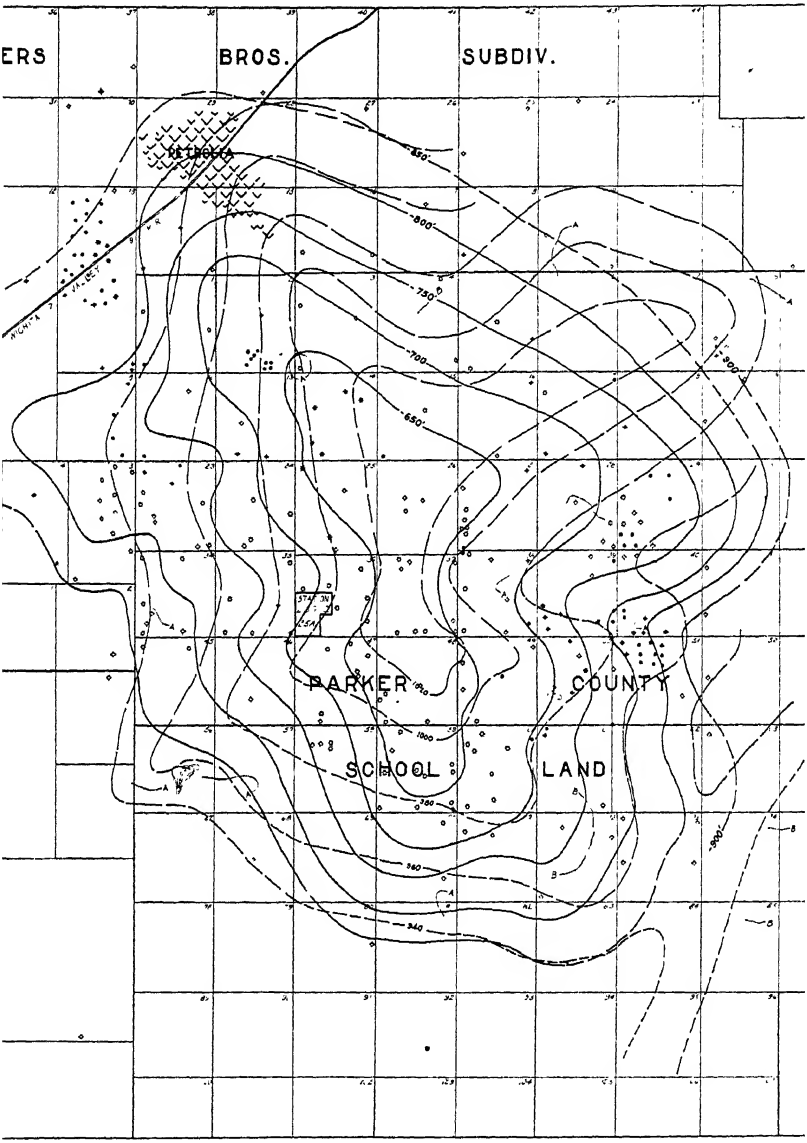


FIG. 2.—Surface and subsurface structure of Petrolia field. Surface (broken lines) contoured on Red-beds; contour interval, 20 feet. Subsurface (solid lines) contoured on lower zone of "big gas" horizon; contour interval, 100 feet. *A*, *B*, outcrops. Width of area mapped, approximately 5 miles.

The Red River arch seems to begin in northeastern Denton County, Texas, where the Blackstock well, near Pilot Point, encountered a heavy body of limestone that was supposedly Ellenburger at a depth of 1,480 feet and drilled continuously in it to a total depth of 1,640 feet. A well 5 miles north of Myra, Cooke County, Texas, penetrated limestone at 1,640 feet and, according to Hager,[1] was still in lime at approximately 3,000 feet. Hager also states that Udden identified samples of limestone from this well as being of Ordovician age.[2] Since the comparatively recent discovery of oil in Cooke County, innumerable test holes have been drilled into this same limestone, and at several locations it has been definitely identified as Ellenburger.

This zone of heavy limestones, sandy limestones, granite wash, and granite extends from these places in Denton and Cooke counties across northeastern Montague County, southern Jefferson County, Oklahoma, northern Clay County, and west through Wichita and Wilbarger into Foard County. Although most deep wells along the ridge have not been drilled through the "Big lime," they have gone deep enough in sufficient number to encounter granite, granite wash, and schist, proving that the ridge has a core of igneous rock. These buried hills are an arch in the Arbuckle limestone which existed there before the overlying beds of younger age were deposited above and on the sides of the ridge. The fact that deep wells only short distances from the arch do not encounter the heavy beds of Ordovician limestone shows that the arch is very steep-sided and that it is somewhat steeper on the north. Beds lower than the Cisco formation, at Petrolia, are deposited against the sides of the arch and thicken considerably away from the crest. Deep wells drilled into these lower beds, around the edges of the Petrolia dome, have encountered thick bodies of sand that contain large quantities of water.

Other major structural features closely related to the Red River arch are the Red River syncline, the Wichita-Arbuckle uplift, and Preston anticline. The Red River syncline lies between the Red River arch and the Wichita-Arbuckle uplift, with an almost due east-west axis. It extends from middle Jefferson County, Oklahoma, westward through Cotton and Tillman counties, Oklahoma. Because of the fact that beds of Canyon, Strawn, and possibly Bend age are deposited against the sides of the older rocks of the Red River arch, it seems certain that the arch was uplifted prior to Bend time. It is now generally accepted that the uplifting of the Wichita Mountains took place not later than Mississip-

[1] Lee Hager, *op. cit.*, p. 64.

[2] Heath M. Robinson, *op. cit.*, p. 292.

pian time,[1] or prior to the uplift of the Arbuckle Mountains. If the Bend formation lies unconformably on the south flank of the Red River arch, it is logical to assume that the uplifting of this arch was contemporaneous with that of the Wichita Mountains.

FIG. 3.—Sketch map of Oklahoma and part of Texas, showing relation of Red River arch to other major structural features.

The Petrolia dome, or anticline, is very pronounced from a subsurface point of view, and dips sharply in all directions from its crest or axis. It is somewhat elliptical in shape and is approximately $4\frac{1}{2}$ miles long and $3\frac{1}{2}$ miles wide at its longest and widest points. This rather abnormal width is due to nosing on the east side and also on the west, where the Petrolia

[1] Frank Gouin, "The Geology of the Oil and Gas Fields of Stephens County Oklahoma," *Oklahoma Geol. Survey Bull. 40-E* (1926), p. 17.

structure joins that of the Martin gas field, which is considered a separate field on account of the synclinal condition between the two.

The subsurface structure (Fig. 2) was mapped on the top of the lower zone of the "big gas horizon" which is found very generally throughout the field at a depth of approximately 1,700 feet. As many of the sands in the Petrolia field are lenticular and discontinuous, it is necessary to classify them as "stray sands." For this reason, correlations were made by grouping the different members of the "big gas horizon" rather than attempting to use any particular member of this or some other group.

The average dip of the 1,700-foot gas zone is approximately 150 feet per mile, measured from the crest of the structure. This formation dips uniformly in all directions from the crest of the dome except toward the west. There it flattens because of a nose which connects it with the Martin gas field, as previously mentioned. Some of the wells in the Petrolia field have been drilled into the "Big lime," but the dip of the lime is greater than that of the producing sands. The interval between the bottom of the producing horizon and the top of the "Big lime" ranges from almost nothing to 230 feet in wells that have reached the "Big lime" on the dome proper. Outside the confines of the dome the lime is not encountered except in very deep wells, and in many places not at all.

RESERVOIR ROCKS

The producing horizons in the Petrolia field consist almost entirely of sands, although in some instances they are sandy shale. These sands are encountered at depths ranging from 150 feet down to approximately 1,750 feet, and for convenience may be classed as shallow, middle, and deep sands. The shallow and middle producing sands are a part of the Wichita formation, and it is practically certain that the deeper production is from the lower part of the Cisco.

Production from the shallow sands has been most consistent from depths of approximately 260 and 350 feet, but there are other intermittent sands, which, because of their lack of continuity, have to be classed as "stray." This shallow horizon, although it has produced considerable oil, is of minor importance, and the area which it covers is small and confined to the highest part of the structure. No production from this level has been found in the outer parts of the field, and very little gas has accompanied the oil.

The middle sands have been most productive at depths of approximately 660 feet and 720 feet, and, as is characteristic of the entire producing section of the field, there are several other sands contiguous to these

depths. Production from this group has never amounted to very much and has consisted almost entirely of oil with small amounts of gas. The middle sands are productive only in a small area on the top of the dome; in this respect they are similar to the shallow sands.

The deep sand horizon, by far the most important in the field, ranges in depth from 1,500 feet to 1,750 feet and is made up of two main producing groups of sands, one at an average depth of approximately 1,550 feet and the other at 1,700 feet. These sands are lenticular and cannot be traced for any great distance, but, by grouping the different members, it is possible to get a zone that is fairly uniform throughout the field. This is what is generally known as the "big gas horizon," and from it has come all the gas of commercial importance and a large part of the oil. A few lenticular sands encountered at depths less than 1,500 feet have been productive, but as a general rule production did not continue and was of little value. As an example Miller No. 9, on the south side of the field, found gas at a depth of 1,130–1,133 feet. The flow was estimated as varying from 10,000,000 to 15,000,000 cubic feet, but a well was never completed in this particular sand. Miller No. 8, same lease, made a seemingly good well in a stray sand from 1,382 to 1,400 feet but lasted only a short time. The significant fact about these showings is that they were not present in any of the adjacent wells, thus proving the lenticular nature and discontinuity of some sands in the field.

An explanation of the discovery of gas in large quantities in these stray sands probably lies in the fact that there is no definite cap rock in the Petrolia field. Formations above the "big gas horizon" consist chiefly of clays, shales, and sands; consequently, there may have been considerable seepage of gas from lower to upper sands. Especially is this true in the innumerable wells that were carelessly drilled, permitting gas to escape from lower sands. The manner in which this occurs is shown by the recent action of Skelly No. 5, on the south side of the field. This well was abandoned in September, 1923. In March, 1928, it began to show gas, and upon being cleaned had an open flow of approximately 25,000,000 cubic feet of gas from an upper sand that evidently showed no gas when the well was drilled. Within a period of two weeks the gas had decreased to less than 500,000 cubic feet and gradually ceased again.

RELATION OF ACCUMULATION TO STRUCTURE

Had the Petrolia field not been discovered until several years later than it was, there is no doubt that its discovery would have been due to the science of geology rather than to accident, as was stated in a fore-

going paragraph. Nevertheless, there is probably not a more perfect example, in that part of the country, of geological structure being the cause of accumulation of oil and gas. This is true, despite the many fields, located on favorable structure, that have since been discovered in the general area of northern Texas and southern Oklahoma. The fact that the Petrolia structure is a dome of symmetrical proportions, on a buried ridge of older rocks, causes it to be an ideal illustration of the relation of the accumulation of petroleum to structure.

A comparison of the surface and subsurface maps of the Petrolia dome shows them to be very similar in size and extent and quite typical of the buried-hill type of structure. The greatest difference is that the subsurface is much more steeply folded, having a closure of 150 feet or more; and erosion of the only beds that can be used for mapping, from the crest of the fold, has made it necessary to estimate the surface closure as between 40 feet and 60 feet. Another decided feature is a distinct surface nose toward the east and northeast that does not seem to be reflected to any appreciable extent in the lower beds. On account of the symmetrical proportions of the structure and pressure of the gas the encroachment of water has been sure, but gradual, on all sides of the field. At present the main producing horizon is almost entirely flooded, and the only remaining oil or gas that is free from water is contained in lenses at higher levels, having escaped, very probably, from the big sands below.

In regard to buried hills and petroleum accumulation, Powers[1] says:

> Petroleum accumulates in structural reservoirs which are usually located in regional synclinoria. In regions of extremely gentle folding such as the Mid-Continent, the major structures are found to have some special cause for existence, usually they overlie buried hills, and it is these structures in which petroleum accumulation is at a maximum or else entirely lacking.

The Petrolia field is a structure of this particular type in that it overlies the buried hills of the Red River arch. Here the petroleum-bearing horizons extend across the summits of the buried hills, and the deeper sands are deposited against the flanks and are filled with water. The buried hills themselves are not known to contain oil or gas, and it is probable that they do not. However, only one well, Byers No. 41, has penetrated the entire section of Ordovician rocks at Petrolia, and it is not located on the crest of the structure.

Two important questions regarding any productive area are: "Where did the oil and gas come from?" and "How did it get there?" It is known that the Bend formation, a prolific producer in central and north-central

[1] Sidney Powers, *op. cit.*, p. 258.

Texas, underlies a vast expanse of territory south of the Red River arch. Also, this formation is supposed to compose the last 15 feet of section in the Halsell well,[1] 18 miles southwest of Petrolia. It would be natural, therefore, to suppose that the Bend formation is deposited against the south flank of the arch but becomes thinner and finally disappears toward the north. This is substantiated by the fact that there is no Bend on the north flank of the arch, so far as is known, inasmuch as no wells have encountered it. The presence of an unconformity between the "Big lime" of the buried ridge and the overlying beds offered a passage for any oil or gas escaping from the Bend and seeking higher levels. It seems reasonable, therefore, that oil or gas from the Bend may have migrated up this unconformity and lodged in the catchment areas of such structures as Petrolia, Burkburnett, and Electra.[2] This theory will no doubt be questioned by some, but in the light of present available information it seems to be a logical explanation of the source of accumulation in these fields.

From what has been stated in this paper, it is seen that the Petrolia dome would never have existed had it not been for the Red River arch; also, that as a result of the formation of this structure, a perfect catchment area for oil and gas was formed at this place on the arch. Therefore, in conclusion, it may be stated that the presence of oil and gas in this field should be credited to geologic structure and that structure was the direct cause of the accumulation of petroleum in the Petrolia field.

ADDITIONAL LITERATURE

E. W. Shaw and P. L. Ports, "Natural-Gas Resources Available to Dallas," *U. S. Geol. Survey Bull. 716-D* (1920).

Carroll H. Wegemann, "Anticlinal Structure in Parts of Cotton and Jefferson Counties, Oklahoma," *ibid., No. 602* (1915).

M. J. Munn, "Reconnaissance of the Grandfield District, Oklahoma," *ibid., No. 547* (1914).

G. S. Rogers, "Helium-bearing Natural Gas," *U. S. Geol. Survey Prof. Paper 121* (1921).

L. C. Glenn, "Some Paleontological Evidence on the Oil-bearing Horizon at Burkburnett, Texas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 5 (1921), p. 154.

E. W. Shaw, "Gas in the Area North and West of Fort Worth," *ibid., No. 629* (1916).

[1] J. A. Udden and D. McN. Phillips, *op. cit.*, p. 81.

[2] William Kennedy, private report.

SMITH-ELLIS OIL FIELD, BROWN COUNTY, TEXAS[1]

WILLIS STORM[2]
Dallas, Texas

ABSTRACT

Oil-producing conditions in this shallow field are typical of those existing in other fields in this part of Brown County, Texas. The sand producing the high-gravity oil from a depth of about 1,300 feet is lenticular. It is stratigraphically located about 50 feet below the unconformity between the Canyon and Strawn formations of lower Pennsylvanian age. The interruption of the normal northwest dip found in this field is thought to be due more to differential settling than to folding or faulting. Contour patterns based on the top of the Palo Pinto limestone and on the top of the producing sand are shown to bring out the conclusion that contours based on the top of a lenticular sand body do not show the true deformation but, instead, show only the shape and extent of the sand body. Porosity and the amount of true sand in the producing horizon have been the most important factors in the accumulation here. Structural deformation is considered secondary.

For many years, Brown County in central Texas has been a Mecca for independent oil operators who desired shallow oil production at a minimum of expense, and a great many wells—both shallow and deep—have been drilled. However, in the last two years considerably more attention has been given this district, owing to the surprisingly large amount of high-gravity oil produced from a sand at a comparatively shallow depth. The Cross Cut pool development brought forth considerable comment on the initial productions of some of the wells; but when the Fry pool was developed, the eyes of the oil men began to open wider at the sight of wells producing 2,000 barrels daily of 42° Bé. gravity oil from a true sand at a depth of approximately 1,300 feet below the surface.

It is the purpose of the writer to describe the detailed geologic features of the Smith-Ellis pool, which is a little more than a mile northeast of the Fry pool and which was discovered after the Fry producing area was outlined. Both fields are approximately 15 miles northwest of Brownwood, the county seat of Brown County (Fig. 1).

HISTORY

On March 7, 1927, Rosenfield *et al.* (afterward incorporated as the "Forest Oil Company") brought in their Davis No. 1 well with an initial production of about 40 barrels from 5 feet of Fry sand from 1,276 to 1,281

[1] Manuscript received by the editor, May 15, 1928.

[2] 4501 Livingstone.

feet in depth. The location of the well was on a slight surface nosing (Fig. 2) and proved to be at the extreme northeast edge of the later-developed

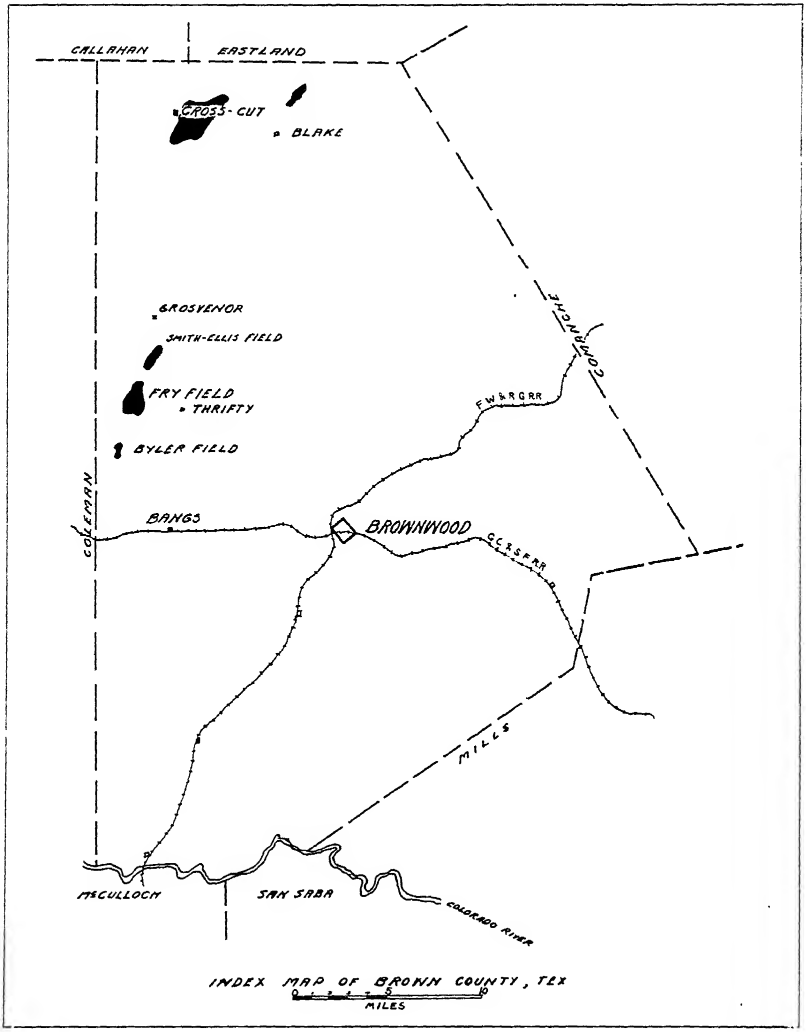


FIG. 1

pool. Previous to the drilling of the Davis well, Rosenfield *et al.* had drilled their Smith No. 1 well southwest of the Davis well and had found a good showing of oil in the Fry sand but were unable to make a producer.

After the Davis discovery they moved south of the Smith No. 1 for their Smith No. 2 well, which proved to be the opening of the main part of the pool. Subsequent drilling has shown that the Smith No. 2 was on the

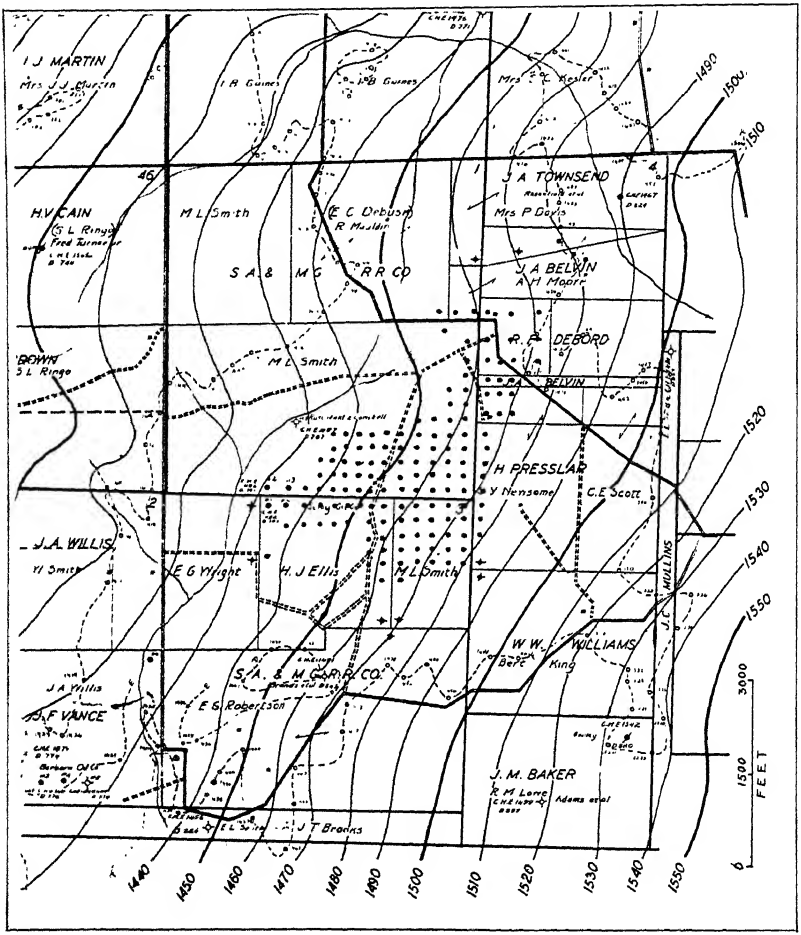


FIG. 2.—Map showing relation of surface structure to production. Surface structure by Hudnall and Pirtle. Contoured on Breckenridge limestone. Contour interval, 10 feet. Datum, sea-level.

extreme west edge of the pool and that if it had been drilled one location farther west it is probable that the discovery would have been postponed indefinitely.

Rapid development followed and 131 producing wells have been drilled to date. Dry holes have practically outlined the pool, and only a few inside locations are left to be drilled.

SURFACE GEOLOGY

Limestones, thin sandstones, and shales belonging to the Harpersville formation of Cisco (upper Pennsylvanian) age are exposed in the area. The Breckenridge and Saddle Creek limestones, excellent datum beds, were used in mapping the surface structure.

As will be noticed on the map made by Hudnall and Pirtle (Fig. 2), the surface structure consists chiefly of normal northwest dip with slight nosings or flattenings and small shallow synclines. It is interesting to observe that the pool is located almost entirely in one of the synclinal areas of the surface structure. Surface structure of the district is considered to be of little value in the present prospecting activities, since more subsurface information is available. In general, the producing structure does not correspond with the surface structure.

SUBSURFACE GEOLOGY

In most of the wells in the field, the first formation encountered is slightly above the Breckenridge limestone. Approximately 280 feet of the Cisco formation of upper Pennsylvanian age overlies 970 feet of the Canyon formation, consisting of thicker beds of limestones and shales, with few, if any, sandstones. Next, the Strawn formation, 580 feet in thickness, consisting mostly of shales with several lenticular sandstone horizons, overlies the Caddo limestone, or Bend, of lower Pennsylvanian age. The Cisco formation is considered to lie unconformably on the Canyon section, and the Canyon in turn unconformably on the shallower-water deposits of the Strawn formation. The Canyon-Strawn unconformity is placed at the base of the Palo Pinto limestone. In the Smith-Ellis pool the hiatus is considered to be more of a disconformity, as comparatively little difference in the thickness of the Palo Pinto limestone or the Strawn formation is observed in this local area. The Fry sand, which is decidedly lenticular, is generally found between 60 and 100 feet below the base of the Palo Pinto limestone (Fig. 3).

The top of the Palo Pinto limestone was used as the contour datum in mapping the structure of the field (Fig. 4). The selection of this datum on which to interpret the structure was made for three reasons. 1. It is the nearest competent bed to the oil-producing horizon and directly above the disconformity. 2. In comparing the sand-thickness map (Fig. 8) and

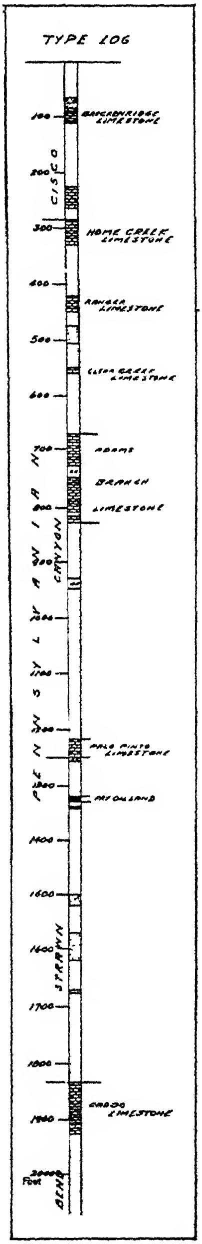


FIG. 3

the contour map, using the top of the sand as datum (Fig. 7), it is found that the thicker parts of the sand lens generally underlie the "highs" that are contoured on the sand-top datum and that the thinner sand areas are beneath the "lows"; for example, using Cranfill and Reynolds' Smith No. 11 and the Shelby Oil and Gas Company's Ellis No. 17 wells, there is a difference of 12 feet in the datum points and only 5 feet in the recorded sand thickness, showing a contoured "low," whereas on the top of the Palo Pinto limestone there is apparently a small "high." 3. In using the top of a known lenticular sand, one does not know which part of the sand has lensed out or thickened, as the case might be. The cross sections (Figs. 5 and 6) show this condition. It is true that a general similarity of contour patterns is obtained by using the limestone and sand data, but the details are important for true structural interpretations, and a limestone datum seems preferable. It is also true that in the drilling of the wells furnishing the necessary data, a steel-line measurement was seldom made until the top of the sand was encountered, thus allowing considerable room for errors in recording the top of the Palo Pinto limestone. However, most of the drillers recognize the hard lime above the sand, and it is doubtful if any great errors exist. As there is no way of correcting these errors in measurement, the geologist must take the data as offered.

In general, the subsurface structure as shown by contours (Fig. 4) and by cross sections (Figs. 5 and 6) may be interpreted as a flattening of the normal northwest dip of 80 feet to the mile. In detail, however, the irregular contour pattern throughout the producing area suggests that differential settling, rather than folding, may have been the more direct cause of the interrupted normal dip, and that the sand body may have been the controlling factor of the settling. Subsurface work on the Palo Pinto limestone east and southeast of this local area has shown that there is a definite small

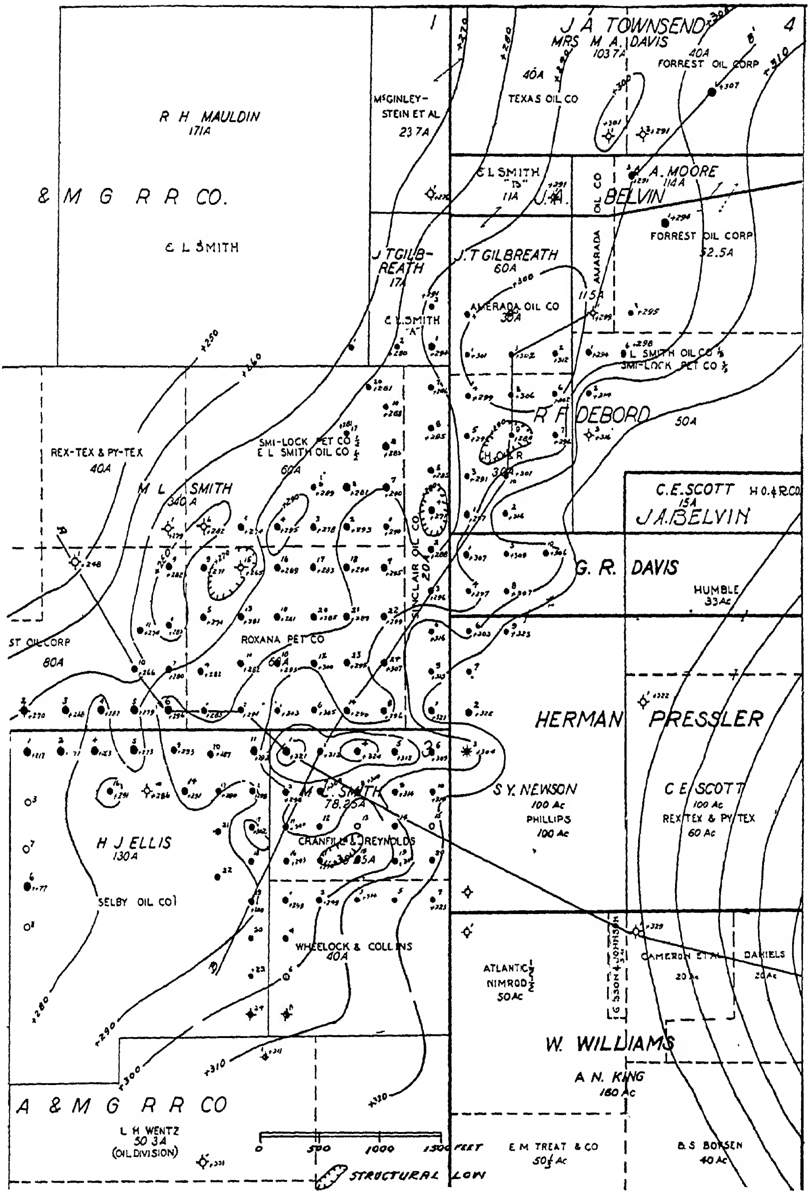


FIG. 4.—Subsurface structure contoured on top of Palo Pinto limestone about 1,200 to 1,250 feet below surface and 90 to 110 feet above top of pay horizon: *A-A* and *B-B*, lines of cross section.

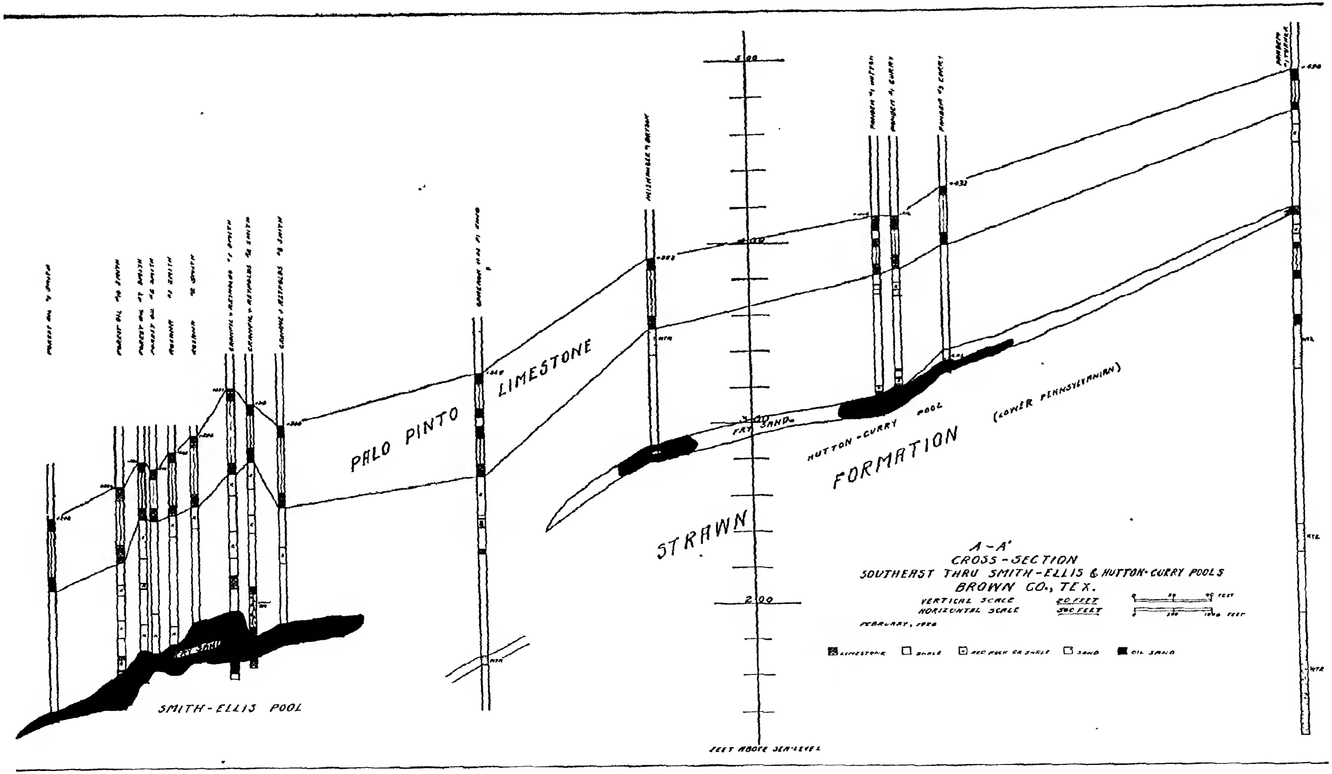

A-A'
CROSS-SECTION
SOUTHEAST THRU SMITH-ELLIS & HUTTON-CURRY POOLS
BROWN CO., TEX.
VERTICAL SCALE
HORIZONTAL SCALE
FEBRUARY
PALO PINTO LIMESTONE
STRAWN FORMATION
(LOWER PENNSYLVANIAN)
HUTTON-CURRY POOL
FRY SAND
SMITH-ELLIS POOL
2200
FEET ABOVE SEA-LEVEL

Fig. 5

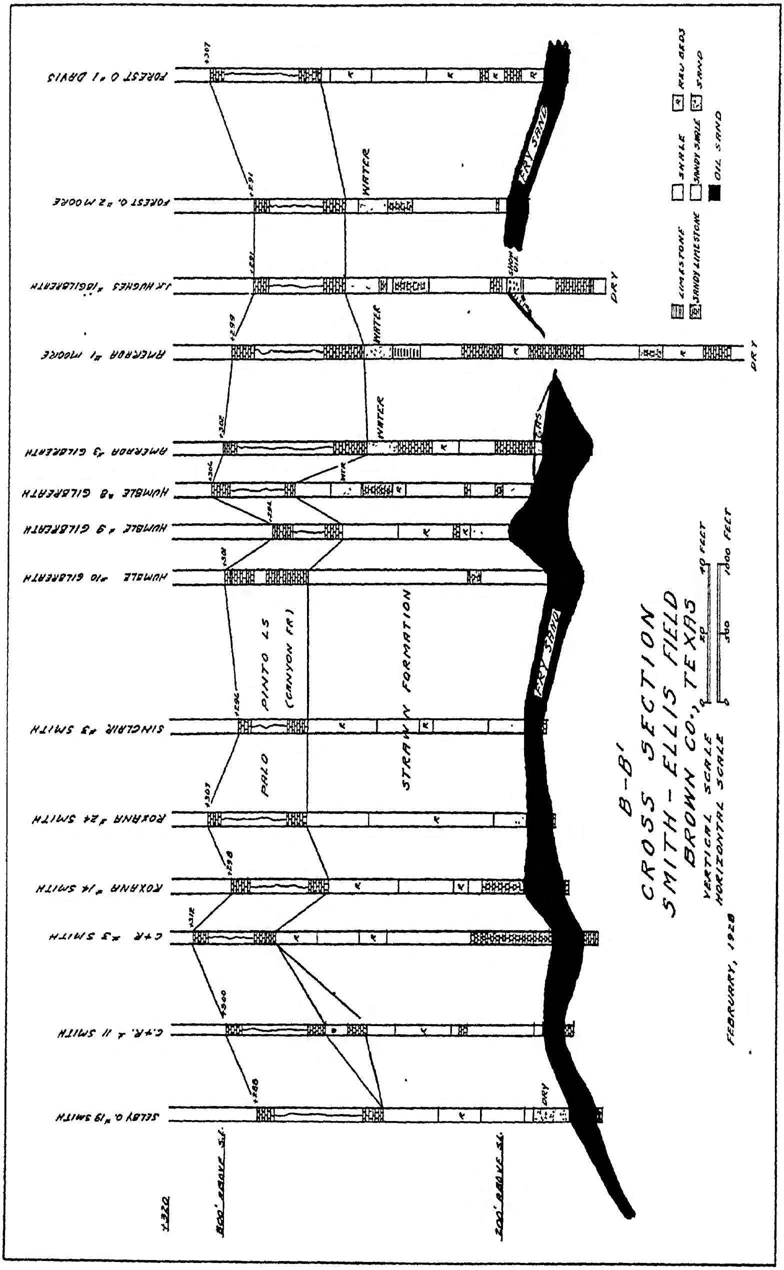

SELBY O. #19 SMITH
C.+R. # 11 SMITH
C+R #3 SMITH
ROXANA #14 SMITH
ROXANA #24 SMITH
SINCLAIR #3 SMITH
HUMBLE #10 GILBREATH
HUMBLE #9 GILBREATH
HUMBLE #8 GILBREATH
AMERADA #3 GILBREATH
AMERADA #1 MOORE
J.K. HUGHES #18 GILBREATH
FOREST O. #2 MOORE
FOREST O #1 DAVIS
+320
800' ABOVE S.L.
200' ABOVE S.L.
PALO PINTO LS
(CANYON FR)
STRAWN FORMATION
WATER
SHOW OIL
GAS
DRY
FRY SAND
B-B'
CROSS SECTION
SMITH-ELLIS FIELD
BROWN CO., TEXAS
VERTICAL SCALE
HORIZONTAL SCALE
FEBRUARY, 1928
LIMESTONE
SANDY LIMESTONE
SHALE
SANDY SHALE
RED BEDS
SAND
OIL SAND

FIG. 6

regional northwest-plunging nose, the axis of which, if projected, would pass through the Smith-Ellis pool; but from present data this small regional nose seems to have disappeared along the projected axis and little, if any, indication of it is present where it would be expected on the west or northwest side of the pool. If there had been any true local folding here, it would seem that (1) the contour pattern would be more regular in design, (2) it would have affected a larger area, and (3) larger regional deformation would be present. Even assuming that many of the irregularities shown could be explained by corrected measurements on top of the Palo Pinto limestone and by corrected surface elevations, the picture would still resemble the results of folding less than it does now. Lacking any direct evidence, let us assume that the irregularities have been caused by small faults. If so, we should find some area not far removed in which considerable folding, or faulting, or both, is in evidence. If the forces which caused the folding of the Bend arch on the east were far-reaching enough to cause local faulting so far from their greatest intensity, it would seem likely that comparatively large folds would be found in the Palo Pinto limestone and in the Strawn formation below. There is no evidence of these folds, although the small regional fold of the Palo Pinto previously mentioned as plunging northwest in the direction of the Smith-Ellis pool is underlain by a slightly more intense nosing of the Caddo limestone (top of the Bend). It is very possible that minor flexures having their origin contemporary with the larger Bend arch on the east could have had some effect on such local areas as the Smith-Ellis field; but it is thought by the writer, with the concurrence of other geologists who have done considerable work in this district, that differential settling has had more to do with the seeming deformation of the local areas than has true folding.

The Strawn formation, in Brown County, is a comparatively shallow sea deposit, consisting principally of calcareous shales, some thin limestones, and fairly regularly spaced sandstone and sandy horizons, of which the Fry oil-sand zone is one, occurring between 60 and 100 feet below the top of the formation. The sandstone and sandy horizons—particularly the Fry—are typically lenticular. In the Smith-Ellis pool, the Fry sand lens (Fig. 8) has an irregular thickness ranging from 1 foot to 30 feet. Considerable calcareous material is present in the sand body, and in places the sand as logged is in fact largely limestone with a small percentage of siliceous material. In other wells, however, fine, pure quartz sand is drilled, and it is from these wells that the largest initial production of oil is obtained. This grading of sand into limestone is a characteristic

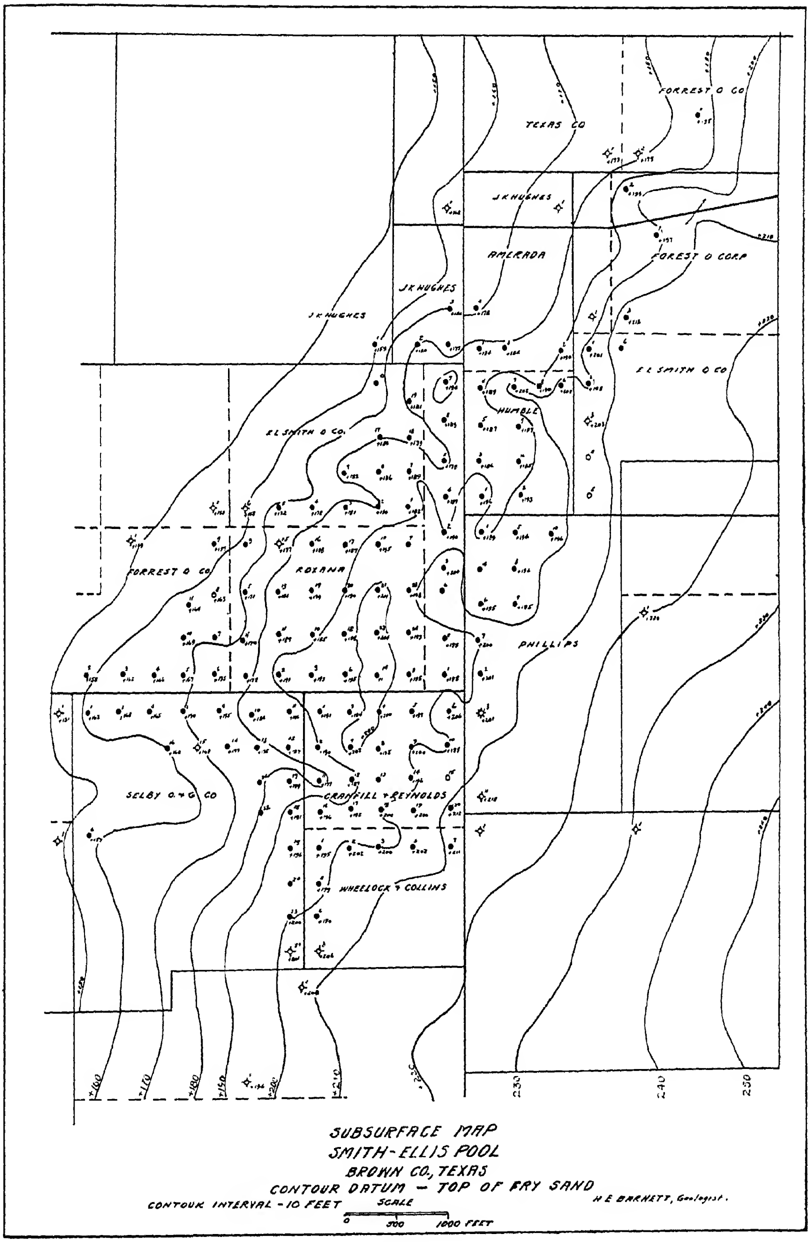

FORREST O CO
TEXAS CO
J K HUGHES
AMERADA
FOREST O CORP
J K HUGHES
J K HUGHES
E L SMITH O CO
HUMBLE
E L SMITH O CO.
ROXANA
FORREST O CO
PHILLIPS
SELBY O. & G CO
CRANFILL & REYNOLDS
WHEELOCK & COLLINS
SUBSURFACE MAP
SMITH-ELLIS POOL
BROWN CO., TEXAS
CONTOUR DATUM — TOP OF FRY SAND
CONTOUR INTERVAL - 10 FEET
SCALE
0 500 1000 FEET
H E BARNETT, Geologist.

FIG. 7

of the Fry sand horizon. In many wells around the edge of the sand body, red or brown shales are found at the expected sand horizon. The shape,

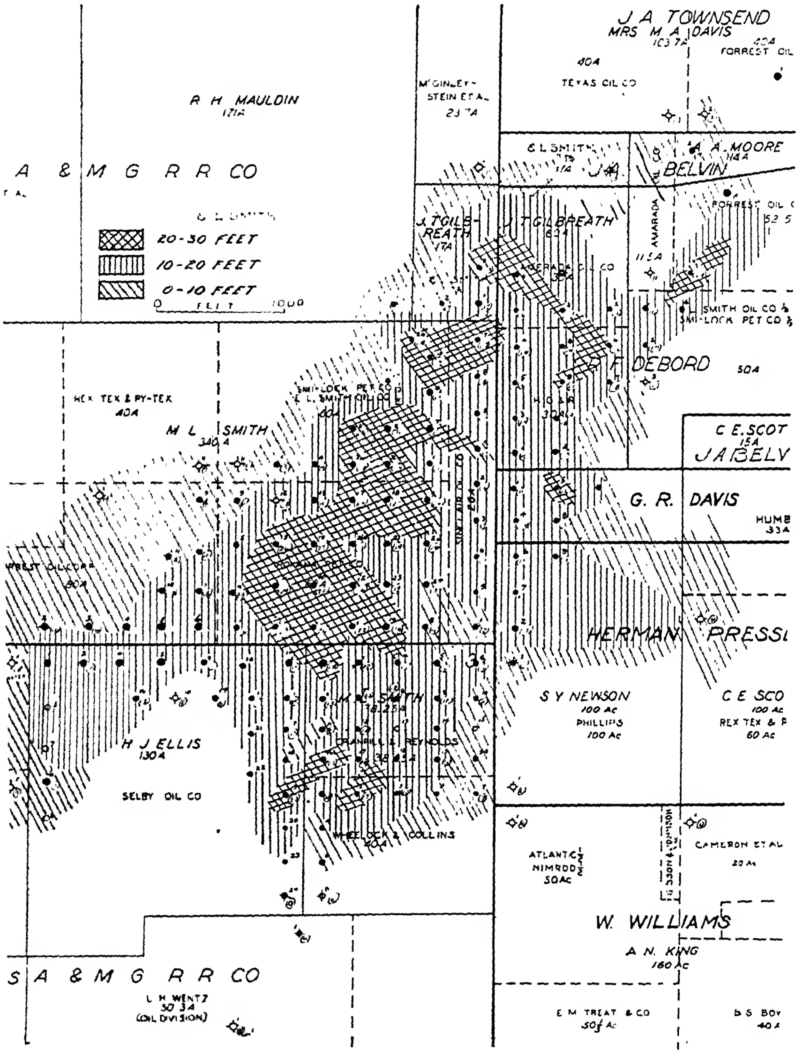


Fig. 8.—Fry sand-thickness map.

irregular thickness, calcareous content, and fine, even-grained lithologic characteristics suggest that the sand deposition occurred in much the

same manner as our present-day spits are formed in coastal marshes. Hubbard and Thompson[1] well described similar conditions of deposition of the principal oil-producing sand in Archer County, Texas.

RELATION OF STRUCTURE TO ACCUMULATION

Structural deformation, whether caused by differential settling, as suggested to be more probable by the writer, or by folding, seems to have been only an indirect cause of the accumulation of oil in this field, since the amount of oil produced evidently depends more on other factors, such as the porosity (depending on the siliceous content of the reservoir and its thickness), than on structural position of the individual wells. By comparing the initial production (Fig. 9) with the sand-thickness map (Fig. 8) and the subsurface map (Fig. 4), it will be seen that the large area of greatest accumulation is somewhat down the normal flank of the locally closed "high" and partly within the area of 20- to 30-foot sand thickness and partly in the adjoining thinner sand area. Other rich spots are observed on small "highs" and in local synclinal areas.

PROBABLE ORIGIN OF THE OIL

In the opinion of the writer, the oil in the Smith-Ellis field probably originated close to where it is found, the shales of the Strawn formation which enclose the sand lens being the source. As brought out by Hubbard and Thompson,[2] the compacting forces exerted during the period of probable differential settling literally "squeezed" the oil, with connate water, from its source into the sand reservoir around which the settling took place. As to whether the migration of the oil was upward or downward into the reservoir, little evidence can be offered. However, it is not thought probable that faulting has aided the process of migration.

PRODUCTION

Since the Davis discovery well was put on the pump, the total amount of oil produced to January 1, 1928, was approximately 846,660 barrels from 366 productive acres and 131 wells, or an average yield of 2,332 barrels per acre. The initial productions ranged from 5 to 1,900 barrels per day, and the average initial production per well computed from 109 wells was 285 barrels. Depths to the sand range from 1,270 to 1,400 feet

[1] W. E. Hubbard and W. C. Thompson, "Geology and Oil Fields of Archer County, Texas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1927), p. 467.

[2] *Op. cit.*

below the surface. The peak of daily production for the field, reached during October, 1927, was 8,300 barrels. The average daily production

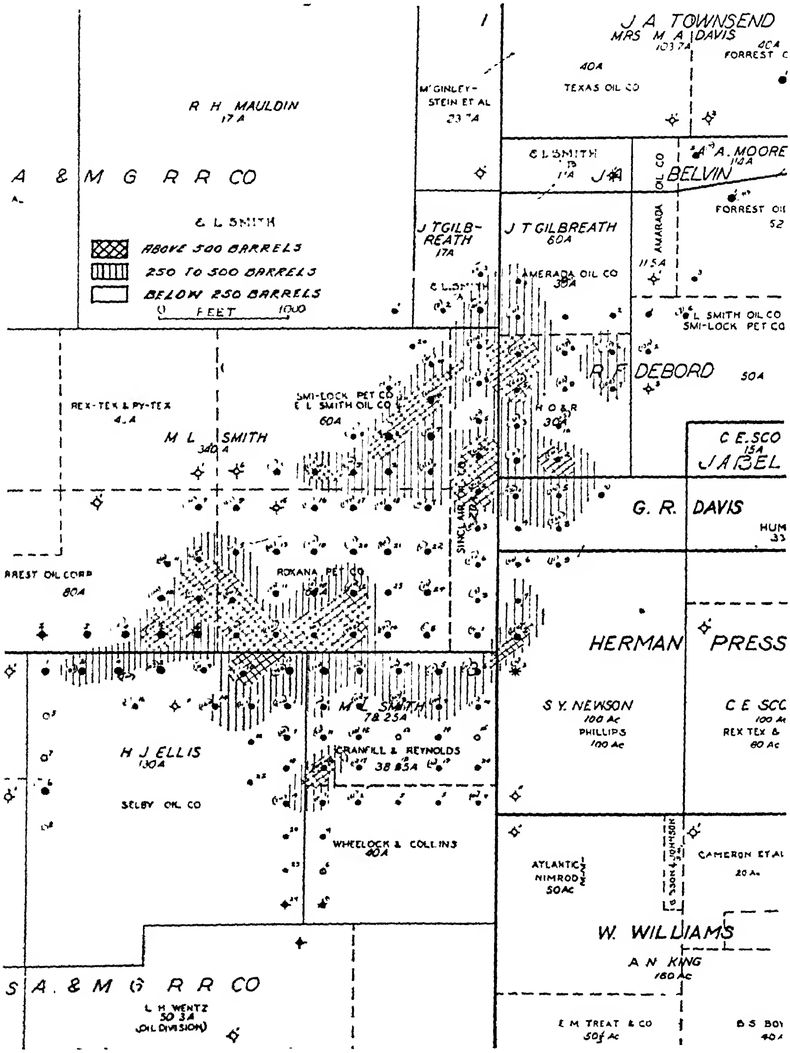


FIG. 9.—Initial-production map.

in January, 1928, was approximately 3,600 barrels. A casinghead-gasoline plant is in operation in the field, taking gas which, from some

wells, contains 4 gallons of gasoline to 1,000 cubic feet of gas. The average gasoline content, however, is about 2 gallons.

Little is known of the reservoir[1] pressure of the wells in the field, but the production of both oil and gas has fallen off rapidly since the wells ceased flowing, which condition, according to a recent article by Heroy,[2] reduces the reservoir pressure in a lenticular sand body to approximately zero when the gas pressure is off the field.

A chemical analysis of the oil is given in Table I.

TABLE I

ANALYSIS OF CRUDE OIL, SMITH-ELLIS FIELD

	Percentage	Gravity (Degrees A.P.I.)
Crude oil	....	42.7
Naphtha	44.6	58.9
W. White	3.7	40.7
Gas oil	21.7	35.1
Bottoms	26.0	23.7
Loss	4.0	....
Bottom settling and water	None	....
Sulphur	0.13	....

WATER ENCROACHMENT

The present water level of the field is about 160 feet above sea-level, and the encroachment is slow. An interesting fact brought to the writer's attention by W. L. Goldston[3] is that the water level in the Smith-Ellis field is approximately 30 feet higher than in the Fry field on the southwest and 30 feet lower than in a recently discovered producing area the same distance northeast. Complete water data have not been compiled.

OPERATIONS

Most of the wells in the field were drilled with the "spudder," a small cable-tool machine operated by a gasoline engine, admirably fitted for the shallow producing areas where considerable limestone is encountered. Some larger machines were used, but few derricks and standard rigs are in evidence. After the wells cease flowing, 2-inch tubing is run and the wells pumped by jacks operated from central-power pumping plants. Casing used in the wells includes 700 or 800 feet of 10-inch and 1,100 or

[1] W. B. Heroy, "Rock Pressure," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), p. 383.

[2] *Ibid.*

[3] Personal communication.

1,200 feet of $8\frac{1}{4}$-inch, and $6\frac{5}{8}$-inch is set on top of the sand. In some wells the $6\frac{5}{8}$-inch casing is cemented on top of the sand; in other wells both the $8\frac{1}{4}$- and $6\frac{5}{8}$-inch strings are left in the hole. Either method seems suitable to protect the sand from top water.

ACKNOWLEDGMENTS

Many thanks are extended to those who assisted the writer in collecting the necessary data for this paper—particularly to John B. Blanchard, who furnished most of the well logs, elevations, and initial productions; to W. L. Goldston for suggestions and the use of the sand-contour map compiled under his direction; and to Hudnall and Pirtle for the use of their surface structure map. Constructive criticism was kindly made by F. H. Lahee.

SYNCLINAL OIL FIELDS IN SOUTHERN WEST VIRGINIA[1]

RALPH E. DAVIS[2] AND EUGENE A. STEPHENSON[2]
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ABSTRACT

Even though West Virginia is the state where the anticlinal theory received its earliest practical application, later developments have proved that the state also contains the outstanding examples of synclinal oil pools. This is especially true in the southern part of the state, where such important synclinal pools as the Tanner Creek field of Gilmer County, the Rouzer pool and the recent Granny's Creek pool of Clay County, a part of the Blue Creek and Clendenin pools of Roane and Kanawha counties, and the Big Creek pool of Lincoln County are located. In the central part of the state the Copley field of Lewis County and the Wolf Summit fields are the major synclinal fields. Some of the synclines are closed structures; others are open.

The following are the important sands which produce oil from synclines: Maxon, Keener,Berea, Big Injun, Weir, and Gordon.

Synclinal oil production is known in several localities in the United States, but within the Appalachian area of West Virginia many such pools occur. Descriptions of several of these fields have appeared from time to time in the publications of the West Virginia Geological Survey. The structure is ordinarily mapped on one of the widespread coal seams as a key horizon.

Three synclinal oil fields in the southern part of the state are described herewith, and maps showing the subsurface structure are presented. The producing horizon in each field is used as the key bed.

GRIFFITHSVILLE FIELD

The Griffithsville oil field in Lincoln County, West Virginia, about 18 miles southwest of Charleston, was discovered in 1908 by the Big Creek Development Company. The major part of development took place rapidly, and the peak of production was soon reached, but the wells proved to be long lived, and after 20 years the field, which covers practically 20 square miles, is still producing about 2,000 barrels of oil per day from approximately 550 wells. The Berea sandstone, about 23 feet

[1] Read before the Association at the Tulsa meeting, March 25, 1927. Manuscript received by the editor, June 1, 1928.

[2] Room 1710, Union Bank Building.

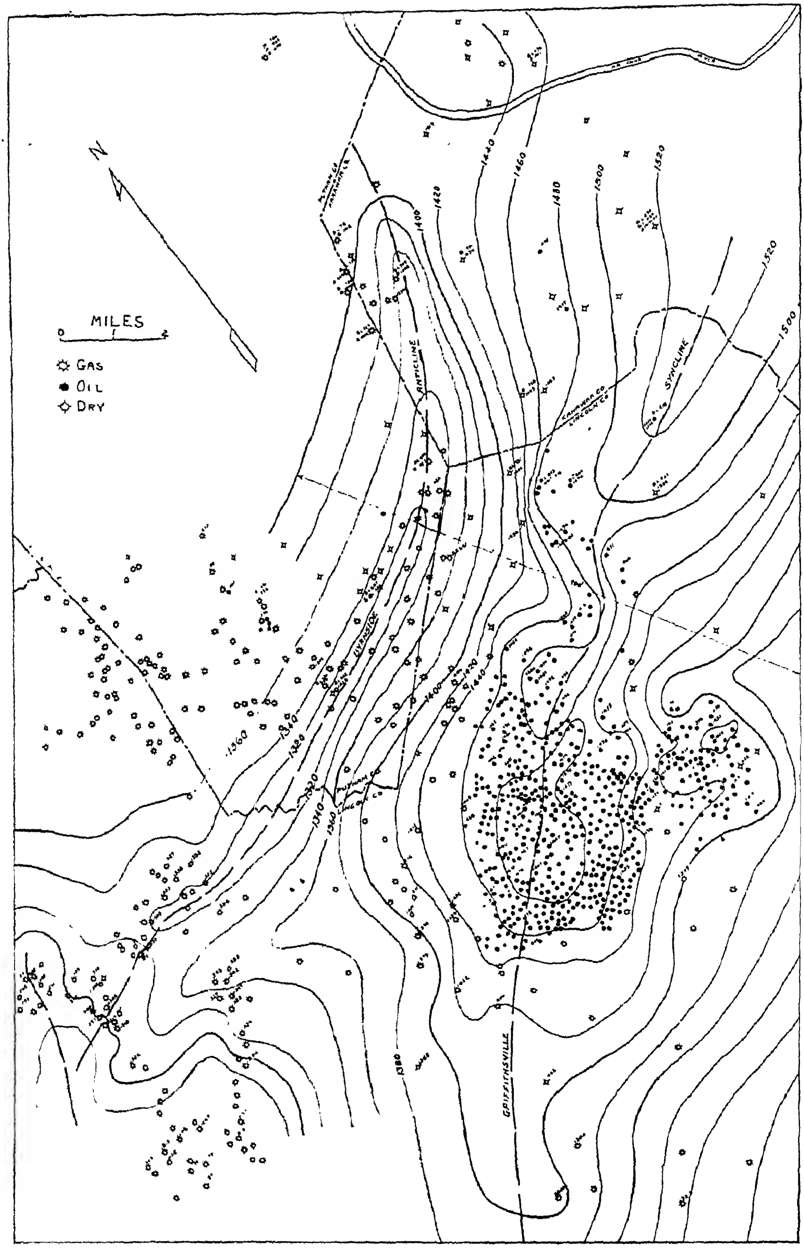

FIG. 1.—Map showing subsurface structure of Big Creek, or Griffithsville, pool, Lincoln County, West Virginia. Contours drawn on top of the Berea sandstone. Contour interval, 20 feet. All contours below sea-level.

thick, is the main oil-producing stratum; it is nearly white in color, fine-grained, hard, and so closely cemented that no very large wells have ever been completed in it. Even though the wells are relatively small and had initial productions which ranged from but 20 to 75 barrels per day, they have maintained a settled rate of production for many years. Practically all of the wells drilled at the time when the field was flush are still producing. The yield per acre has been about 1,400 barrels, but the porosity of the sand, its thickness, and the daily rate of production per well indicate that considerable oil can still be recovered before air- and water-flooding become necessary. Practically no water is produced with the oil.

The structure of the field is definitely synclinal, but the amount of actual closure does not exceed 20 feet, with its major axis trending northeast by southwest; the syncline is in general spoon-shaped. At the bottom of the structure, where the most prolific area is found, the Berea sandstone lies 1,480 feet below sea-level. Oil extends up the sides of the basin to approximately 1,400 feet below sea-level, at which elevation important gas production occurs. The area of gas production nearly surrounds the oil pool, and the gas territory extends southeast almost to the crest of the Warfield anticline and southwest to the Branchland anticline. It constitutes one of the major gas-producing areas of the state (Fig. 1).

TANNER CREEK FIELD

The Tanner Creek oil field, which was opened in 1918, is in the Dekalb district of Gilmer County. Gas and oil had been found previously in scattered wells in this area in both the Big Injun and Berea sands, and gas showings which had been encountered in the Maxon sand had been regarded as of little significance. The completion of a well in the Maxon sand, making 120 barrels of oil per day at a depth of 1,700 feet, stimulated active development in the area; and the limits of the field were soon defined. At present about 200 wells are making, on an average, 1½ barrels per day.

The pool is located in a small basin along the major axis of the Robinson syncline, which, like other anticlinal and synclinal axes in West Virginia, is somewhat undulatory in character. At the site of the Tanner Creek pool, the axis is much higher than toward the northeast and southwest. The structural position of the pool is analogous to that of a small sink hole situated along the divide at the head of two valleys. Several small closed basins occur in the field, and the largest wells have been completed in these smaller basins. It is the most important oil field in the state producing from the Maxon sand (Fig. 2).

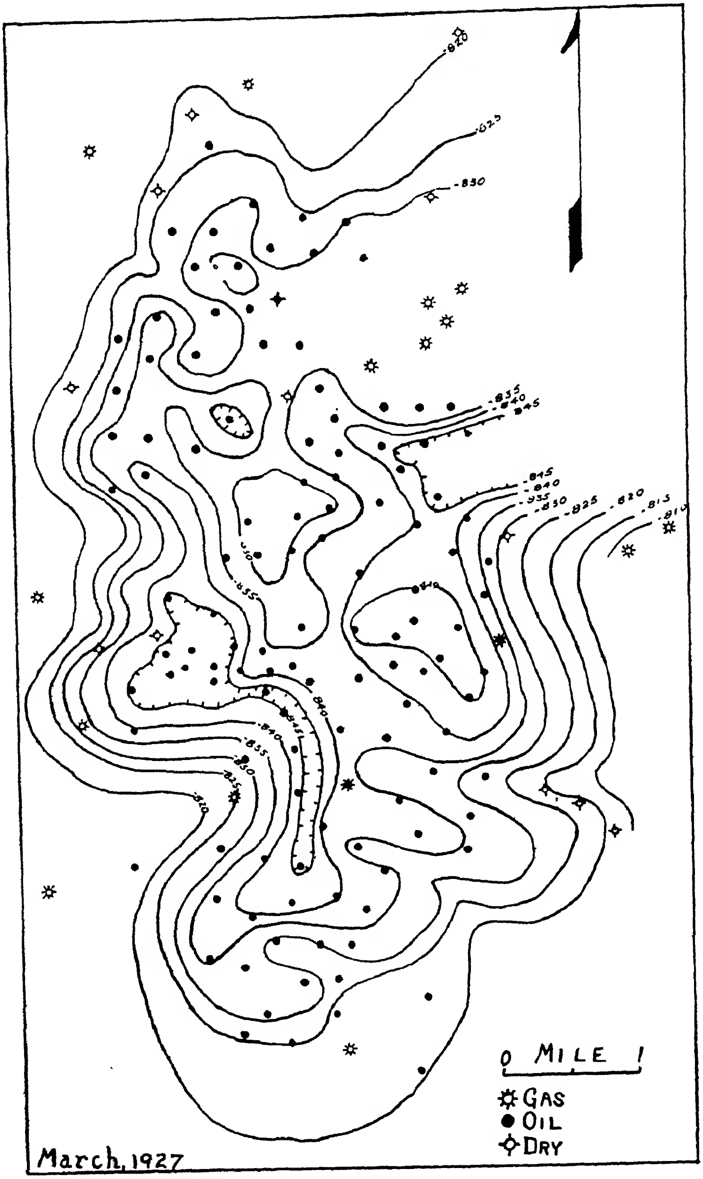

FIG. 2.—Map showing subsurface structure of Tanner Creek pool, Gilmer County, West Virginia. Contour interval, 5 feet. Contours drawn on top of Maxon sand. All contours below sea-level.

GRANNY'S CREEK FIELD

In Clay County, a small pool near Elk River called the Rouzer pool has produced oil from the Keener sand for many years, but the wells

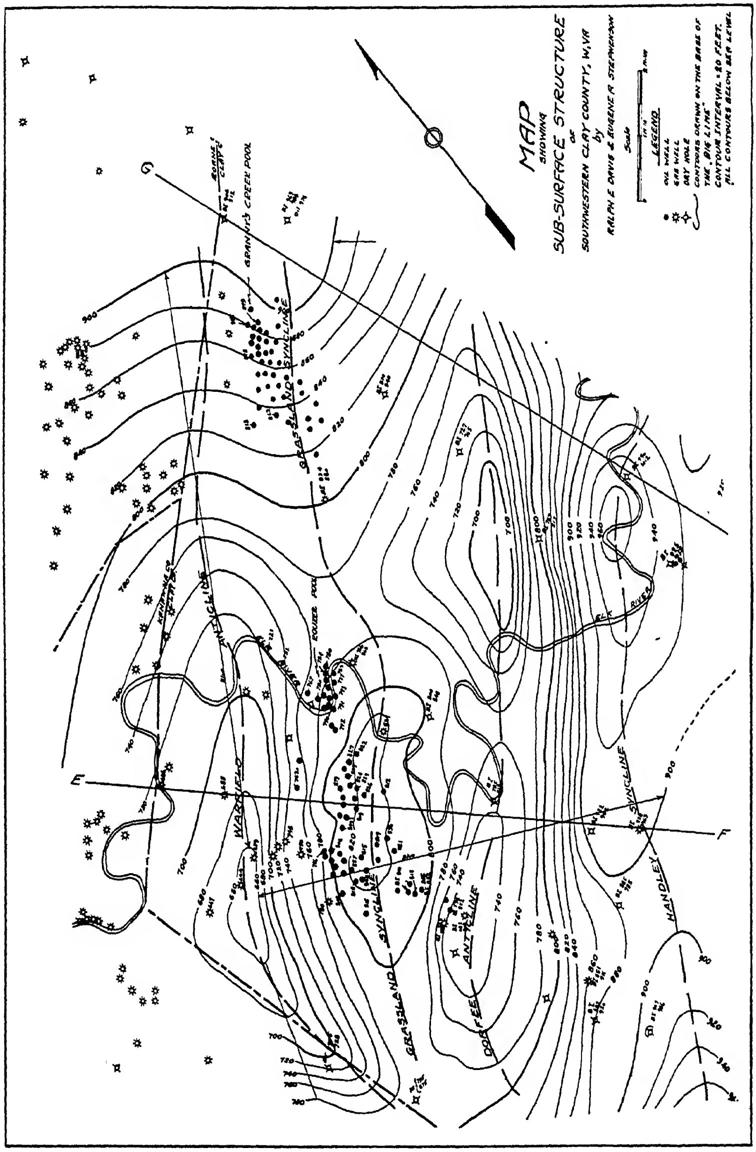

FIG. 3.—Map showing subsurface structure, southwestern Clay County, West Virginia. Contoured on base of Big lime. Contour interval, 20 feet.

have all been small and the productive area limited to about 4 square miles. However, operations in this pool made it possible to prepare, in 1923, a detailed subsurface map of the area, contoured on the Keener sand; and the results indicated a possible extension of the producing area toward the northeast, beyond the closed area, to a point where the axis of the syncline plunged downward again. Prospecting in this direction was followed by the development of a second pool, which has been called the Granny's Creek pool.

Production in the Granny's Creek pool, which also produces from the Keener sand, is obtained at depths which range from 1,600 to 2,000 feet. The initial production of wells ranges from 30 to 50 barrels per day. The sand is about 25 feet thick. The limits of the field are not yet defined (Fig. 3).

WATER CONDITIONS

The Berea sand is characteristically free from water, and in the Griffithsville syncline wells in the very bottom of the trough produce no water.[1] In the Big Injun horizon, the sand of one syncline near Clendenin is saturated with water and no commercial oil is obtained. In Clay County, where the Granny's Creek synclinal pool is located, the Big Injun is free from water. Several of the pools farther north, such as those along the Robinson synclines, are also free from water. No special explanation for the occurrence of oil under these conditions is needed, since it is in accord with the theory of oil accumulation as announced long ago both by White and by Hunt. However, we are confronted with the need of some adequate explanation for the absence of water in these sands.

[1] The field men state that if the wells made a little water it would help to clean the sand.

ELK BASIN OIL AND GAS FIELD, PARK COUNTY, WYOMING, AND CARBON COUNTY, MONTANA[1]

JOHN G. BARTRAM[2]
Denver, Colorado

ABSTRACT

The Elk Basin oil and gas field on the state line between Wyoming and Montana is on a large anticline in formations of Upper Cretaceous age. Oil production comes from sands in the Frontier formation, and gas from the sands of the Dakota group. The structure is broken by three sets of normal faults with displacements ranging from a few feet to 700 feet. The south end of the field is an excellent example of the accumulation of oil in fault blocks. The field was discovered in October, 1915, and the total production to January 1, 1927, was 8,120,000 barrels. The field is now being revived with a unified gas drive. There are untested possibilities for oil and gas in deeper formations.

INTRODUCTION

This report on the Elk Basin field, in Park County, Wyoming, and Carbon County, Montana, is largely compiled from the work of several other geologists, who followed the development of the field and who prepared reports for the Midwest Refining Company and other companies. In particular, the work of E. L. Estabrook and H. T. Morley is acknowledged, but credit is also due to several other geologists.

The Elk Basin oil and gas field has not been described in detail, although reference has been made to it in numerous publications. The anticline was located and discussed in several coal reports of the U. S. Geological Survey[3] before it was drilled for oil. A paper by Estabrook[4] described the faulting and its relation to production.

[1] Presented before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, August 12, 1928. Published by permission of the Midwest Refining Company.

[2] 2555 Clermont St.

[3] C. A. Fisher, "Coal of the Bighorn Basin in Northwest Wyoming," *U. S. Geol. Survey Bull. 225* (1904), pp. 345–64; C. A. Fisher, "Development of the Bear Creek Coal Fields, Montana," *ibid., No. 285* (1906), pp. 269–70; C. W. Washburne, "Coal Fields of the Northeast Side of the Bighorn Basin, Wyoming, and of Bridger, Montana," *ibid., No. 341* (1909), pp. 165–99.

[4] E. L. Estabrook, "Faulting in Wyoming Oil Fields," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 7, No. 2 (March–April, 1923), p. 95.

PHYSIOGRAPHY

Elk Basin is a natural basin or park, surrounded by rough sandstone hills ranging from 400 to 500 feet in height. The softer and less resistant Cody shale is exposed on the axis on the high part of the anticline and has been eroded to form the basin, but the harder sandstones of the Eagle and Mesaverde formations have produced an escarpment or rim rock that dips away in all directions. The central part of the field is rolling, fairly level ground, but the south end and sides are rough and rather inaccessible.

Elk Basin is in the north end of the Big Horn Basin, one of the main physiographic units in Wyoming, and is about equally distant (25 miles) from the Beartooth Mountains on the west and the Big Horn Mountains on the east. In both these ranges all the sedimentary formations crop out at elevations higher than the field.

HISTORY

The first well in Elk Basin was completed in October, 1915, by Jim Hurst *et al.*, who later organized the Elk Basin Petroleum Company, which merged with the Mutual Oil Company and later with the Continental Oil Company. The well was located by C. A. Fisher and found oil in the First Wall Creek sand. Fisher had previously shown the anticline on coal maps of the U. S. Geological Survey. The entire development of the field has been under advice of the geological departments of the several companies interested.

Recently, when the field had reached a low production, a unified gas drive was started, which is being carried out under the direction of production engineers.

STRATIGRAPHY

The stratigraphic section of this area has been amply described in many publications and need not be repeated in detail.[1]

The Mesaverde and Cody formations are exposed at Elk Basin. The surface mapping was done on the Eagle sandstone in the upper part of the Cody shale and on the lowest sandstones in the Mesaverde formations. These beds are easily mapped and furnished excellent control, particularly in the study of the many faults. The outcrops along the top of the anticline are soft shale and cannot be mapped with any certainty, so that the central part of the field has been detailed entirely on subsurface beds.

[1] D. F. Hewett, "Geology and Oil and Coal Resources of the Oregon Basin, Meeteetse, and Grass Creek Basin Quadrangles, Wyoming," *U. S. Geol. Survey Prof. Paper 145* (1926), p. 11.

The two important subsurface key beds are the First and Second Wall Creek sands in the Frontier formation. All the producing wells have drilled to one or both of these horizons. As there are no sandstones in the shale above the First Wall Creek sand, its identification is very positive. The First sand contains much sandy shale, is fairly thick, and irregular, so that its exact top or bottom is indefinite in many wells. The Second sand is a thinner but more definite and regular bed; therefore it has been used for contouring subsurface maps.

The Cody shale, as shown by wells at Elk Basin, has a thickness ranging from 1,100 to 1,800 feet above the First sand. The shale is laminated. Its color ranges from dull blue to dark gray or olive gray. Marine fossils are fairly plentiful, and *Foraminifera* and prisms of *Inoceramus* shells can be found in most well samples. The First Wall Creek sand is composed of shaly sandstone and sandy shale ranging from 75 to 100 feet in thickness. Below it there is approximately 135 feet of blue shale to the top of the Second Wall Creek sand, a clean, uniform sandstone approximately 40 feet thick that has produced most of the oil in the field. About 200 feet below the Second Wall Creek sand is the so-called "Third Wall Creek" sand, which is merely a zone of sandy shale that is very irregular but has given showings of oil and gas.

Approximately 1,000 feet below the Second Wall Creek sand is the Dakota or Cloverly group of coarse sandstones, conglomeratic in places. These good reservoir beds directly underlie the marine

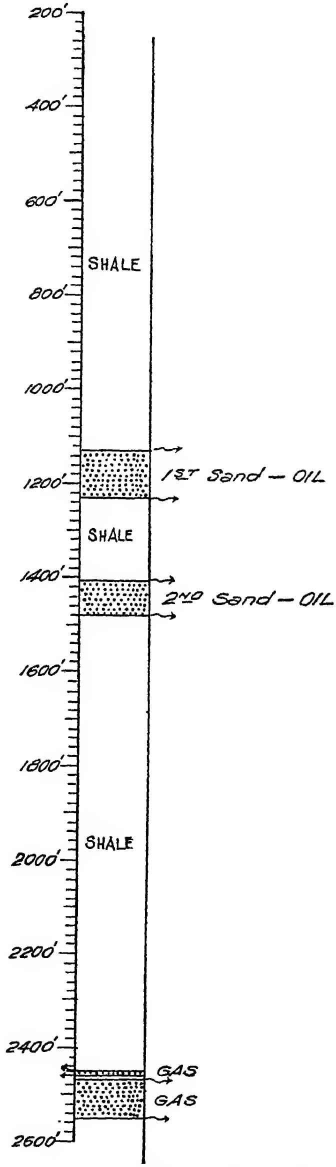

FIG. 1.—Stratigraphic section of oil and gas horizons made from typical logs in Elk Basin field. Depths in feet.

Cretaceous shales and are producing gas at Elk Basin. The exact thickness of sand in the Cloverly group is unknown, since it has not been fully penetrated in any well, but the thickness probably exceeds 100 feet.

Beneath the Cloverly the formations have not been penetrated, but the Morrison, Sundance, Chugwater, Embar, Tensleep, and Amsden formations will be found in regular order. The Morrison consists of approximately 375 feet of purple, reddish, and green-gray shale with some interbedded, irregular sandstones that might produce gas or even oil. Beneath these are the greenish-gray shales and sandstones with a little marine limestone of the Jurassic Sundance formation, 550 feet thick, which has recently become an important producer in other fields in Wyoming and Colorado. The next formation is the Chugwater of Triassic age, about 900 feet of red beds, which are practically of no significance for oil. The next lower beds are the relatively thin Embar limestone, Tensleep sandstone, and Amsden limestones, sandstones, and red beds, 170, 210, and 300 feet thick, respectively. The Embar and Tensleep of Carboniferous age produce black oil in central and northern Wyoming and may be productive at Elk Basin.

Oil and gas in commercial amounts have been developed in the First and Second Wall Creek sands, and gas in the Dakota or Cloverly group of sands. The lower formations are still untested, but it is probable that some of them will produce gas or oil. The sands of the Morrison and Sundance formations are very probably gas-bearing, and the Embar and Tensleep formations may contain either black oil or gas.

The various sandstones deposited in the Cretaceous sea had their source on the west and were spread out as great sheets that extend from New Mexico and Colorado on the south far into Canada on the north. Toward the east all of them, except those of the Dakota or Cloverly group, thin and disappear at different points. The Dakota or Cloverly sandstones were the basal sandstones of the invading Cretaceous sea and were deposited throughout almost all the Rocky Mountain area,

At Elk Basin all the formations are fairly competent, so that the folding and faulting have occurred with almost no distortion of the beds. Even the thick Cretaceous shales have been folded evenly and have proved quite competent.

SURFACE STRUCTURE

In Wyoming, all the main mountain ranges are large eroded anticlines or faulted anticlines, and the intervening basins are vast synclines. The Big Horn Basin is a syncline more than 150 miles long by 70 miles wide and is between the Big Horn Mountains, a large anticline, on the east, and the Beartooth and Absaroka ranges, a more complex system of fold-

ing, thrust faulting, and volcanics, on the west. Around the edges of the basin are many smaller anticlines, whose axes nearly parallel the mountain folding. The regional relations can be studied best on the new *Geologic Map of Wyoming*, published by the U. S. Geological Survey. Practically all the folding occurred at the close of Cretaceous time and was accomplished by a great thrust movement from the west, as evidenced by the many faults that overthrust from the west in western Wyoming, Idaho, and Montana. West of Elk Basin, the Hart Mountain overthrust pushed outward for many miles and left Paleozoic limestones on top of Upper Cretaceous coal-bearing rocks.

The Elk Basin anticline is on the east side of the Big Horn Basin, near its north end. It is on the east side of the major syncline, and the normal dip is 5°–10° SW. The long axis of the anticline extends northwest and southeast. It is symmetrical, and the dips on both the northeast and southwest flanks range from 10° to 24°. The steepest dips are in the northeast quarter of Sec. 24, T. 58 N., R. 99 W. The closure of the structure in the area mapped is at least 800 feet, but the total closure is probably two or three times that amount. The limiting syncline is on the east, where the structure has not been mapped in detail and where much of the geology is obscured by recent gravels. The area within the closure is much more than 4 square miles, and the area from which oil could accumulate is 100 square miles.

SUBSURFACE STRUCTURE

The subsurface structure conforms to that on the surface as nearly as can be determined.

The structure of the top part of the anticline can not be mapped in detail on the surface or on the First Wall Creek sand, so that the only accurate maps are on one horizon, the Second Wall Creek sand (Plate 1). If many wells are drilled to the Dakota in the future, it should be possible to determine whether there is convergence of beds; but none is expected. The axis of the anticline is so broad and the dips on the sides so gentle that the subsurface axis appears to be directly beneath the surface axis and the axial plane must be nearly vertical.

The deformation took place at the close of Cretaceous time, when all the formations in Wyoming and adjacent areas were subjected to lateral compression, which originated on the west.

FAULTING

The Elk Basin anticline is broken by three distinct sets of normal faults and is perhaps the best place in Wyoming to study faults and their relation to oil and gas accumulation. They have been described by Esta-

below the Morrison, it will be support for Irwin's theory that they are largely due to settling in the shaly and more compressible formations. If they continue down through the harder beds, the tension theory will seem the most reasonable.

In the main part of the Elk Basin field, the faulting has not greatly affected the accumulation of petroleum, since there was enough oil to fill the sands both in the upthrown and downthrown blocks. The oil-water contact on the edge of the field is broken somewhat by the faults, but really not as much as would be expected. In the south end of the field, faults have been important factors in the accumulation of oil and gas. Commercial accumulations of oil and gas have been developed on the high parts of four fault blocks with practically barren areas between three of them. Production is continuous between the two northernmost blocks. In the upthrown blocks oil and gas are found in the First and Second Wall Creek sands exactly as on top of the anticline.

Faults may be more important in the gas pool that is being developed in the Dakota group of sands. Only three wells (No. 23-A, Elk 6, southwest quarter of Section 19, and No. 21 and No. 23, Elk 3, southeast quarter of Section 24) have been drilled into the Dakota gas sands, but they have yielded a large amount of gas that has been piped and sold in Billings, Montana. The decline in rock pressure has been much more gradual than was figured theoretically on the basis of an assumed area greater than the oil field and the average thickness and porosity of the same sands at the outcrop and in other fields. The gradual decline may mean either that the gas pool in the Dakota sands is directly connected through faults with other pools in sands of the Morrison and Sundance formations, so that the wells drain more than the one group of sands, or that water is following the gas up into the anticline as the gas is drained, and the water pressure is holding up the gas pressure. When wells are drilled into the Morrison and Sundance sands at some later date, the presence or absence of gas in those sands and the relation of the gas pressure there to that of the Dakota sands will answer this question.

Even with the large number of faults in Elk Basin, there are no known seeps of oil or gas, and the different sands had normal rock pressures when first drilled into. The 1,100 feet of blue shale between the surface and the First Wall Creek sand was sufficient to seal the faults effectively, and the 1,000 feet of shale between the Second Wall Creek and Dakota sands prevented migration there. Since the intervals between the Dakota and the Morrison and Sundance are much less than those above, it would be easier for gas to migrate between them.

RESERVOIR ROCKS

The reservoir rocks in the Elk Basin field are all sandstones or shaly sandstones. The First and Second Wall Creek sands are members of the Frontier formation that extends uniformly throughout central and western Wyoming and throughout small parts of Colorado, Montana, and Utah. The sediments came from a source west of Wyoming, probably in central Utah. The formation is a very thick series of sandstones, shales, and coals with some conglomerate in northeastern Utah and southwestern Wyoming. The formation thins toward the northeast, east, and southeast. Elk Basin is far out toward the northeast edge of the Frontier sands, and the First Wall Creek sand contains much shale and is really more of a sandy shale than a sandstone. It thins and disappears in Montana northeast of the field. The Second Wall Creek sand is 40 feet of good sandstone and is a more continuous and uniform stratum that extends farther than the remainder of the sandstones. The other sandstones of the Frontier formation are represented at Elk Basin only by the thin sandy shale that has been called the "Third Wall Creek" sand.

The wells in the Elk Basin field were almost all drilled from seven to twelve years ago before geologists did much subsurface work, and practically no samples of well cuttings were saved. There are now no complete samples from any well, and complete descriptions of the beds cannot be made. The descriptions of the Wall Creek and Dakota sands are composite, made from samples of outcrops and fields near by. The porosity of the Wall Creek sands in other fields ranges from 15 to 20 per cent. The First Wall Creek sand at Elk Basin must have a much lower porosity and probably does not exceed 10 per cent, at most, since it contains so much clay. The Second Wall Creek sand probably has a porosity ranging from 18 to 20 per cent, but no samples are available for tests, and it cannot be accurately determined. The Frontier sands have a relatively uniform size of grain (0.12–0.16 millimeter); and the grains are angular, though a few are subround. Quartz constitutes the main bulk, the feldspars rank next, and there are only very small amounts of the minerals zircon, tourmaline, biotite, and chlorite. There has been alteration of the minerals by meteoric waters, as biotite has been altered to chlorite and feldspar to kaolin. Calcite and quartz are present as cementing materials; and where calcite has been deposited, the sand is very tight. Secondary quartz is not plentiful.

The Dakota sand is similar in character to the Wall Creek sands except that the grains are ordinarily much larger (0.24–0.45 millimeter) and they are subangular and subround. The lowest sand of the Dakota group is coarser and is conglomeratic in places.

The source of oil and gas in the Wall Creek and Dakota sands is generally believed to be the marine Cretaceous shales with which they are in direct contact. These shales are rich in organic material, and there is no reason to consider any other source. The oil probably originated locally and did not have to migrate far, although there is a large area (100 square miles) from which oil could have accumulated into this anticline.

RELATION OF ACCUMULATION TO STRUCTURE

In the Big Horn Basin there are many large structures with closures ranging from a few feet to more than 2,000 feet, but only part of them have produced oil and gas. This has caused much discussion, and many theories have been advanced to explain why one anticline was productive and another near by was barren. Most of these theories depend on presence or absence of source material, size of area from which oil could accumulate, and movement of water, which might flush the oil out of some folds. Recently the amount of faulting has also been suggested as an important factor. These will not be discussed in detail in this paper.

The oil fills the top of the fold in the First and Second Wall Creek sands and extends uniformly down all sides. The First Wall Creek sand is so shaly and relatively non-porous that there is practically no water in it, and oil and gas are found in it only here and there where the porosity permitted accumulation. Thus, oil in small amounts has been found far down the sides of the anticline.

The Second Wall Creek sand, a more porous, uniform sandstone, contains water below the oil, and there is a well-marked water level in the field. In the main part of the field no gas wells have been found in the Wall Creek sands, but gas has been found in the fault blocks in the south end. In this locality gas occurs in the First Wall Creek sand on the high part of the block with oil below it. In the Second Wall Creek sand there is water below the gas, with evidently no oil between, although not enough wells have been drilled to remove the possibility entirely. With only three wells to the Dakota sands on top of the structure, little can be said about the relation of accumulation to structure, other than that there is a tremendous amount of gas on the crest of the fold in those sands.

OIL

The Elk Basin oil is green in color, with a gravity of approximately 39.5° Bé. and a Saybolt Universal viscosity of 37 seconds at 60° F. The oil is uniform throughout the field, except in the faulted south end where the gravity is somewhat higher; and the oil contains some sulphur.

GAS

Casinghead gas occurs with the oil from the First and Second Wall Creek sands and has intermittently supplied a casinghead-gasoline plant in the field. Detailed figures on this gas are not available. The expansion

TABLE I

CHEMICAL ANALYSIS OF AN AVERAGE ELK BASIN CRUDE OIL

	Percentage
Gasoline	42.0
Kerosene	11.0
Gas oil	9.0
Heavy distillate	36.1
Coke	1.9
	100.0

of this gas and the resultant cooling have caused much trouble with paraffin, and it is necessary frequently to remove the paraffin from the tubing of the wells.

The gas in the Dakota sands had an original closed-in rock pressure of about 925 pounds, which is nearly a normal hydrostatic pressure for the depth of 2,400 feet.

TABLE II

ANALYSIS OF GAS FROM DAKOTA SANDS

	Percentage
Methane	89.4
Ethane	10.0
Carbon dioxide	0.6
Total	100.0
Specific gravity	0.615
B.T.U.	1,078

WATER

There have been no serious water problems at Elk Basin, because there is neither top nor bottom water, and only edge water in the Second Wall Creek sand. This water is not under much head and has encroached very little, although the field has been productive for twelve years. Accurate information is not available about the water pressure, but water fills up very little in the wells. With water only on the edge of the field, there can be practically no coning of water in the oil sands. An analysis of a typical Second Wall Creek sand water is given in Table III.

OIL AND GAS PRODUCTION

All the wells at Elk Basin have been drilled with standard tools; many with portable drilling machines. The drilling has been easy and cheap, because only firm but soft shale is encountered down to the First Wall Creek sand; then sand, sandy shale, and shale to the Second Wall Creek sand. As there is practically no water in the First Wall Creek sand, there have been no casing problems. The wells flowed naturally at first, then were pumped for many years. Recently gas has been introduced into key wells and forced back into the sand in a unified gas drive. This seems to be getting results, and the production of the field has increased from 600 to 1,100 barrels per day within the past year, largely due to the gas drive. It is impossible to predict the life of the field now, as accurate decline curves cannot be drawn until the production reaches a new peak and starts to decline again under the gas-drive methods, but the field should be a consistent producer for many years.

TABLE III

Analysis of Water from Second Wall Creek Sand, Midwest Refining Company's No. 11, Lease Elk No. 8
Sec. 25, T. 9 S., R. 23 E., Montana

Constituent	Parts per Million
Sodium sulphate	7.6
Sodium chloride	8,160.0
Sodium carbonate	66.0
Calcium carbonate	46.4
Magnesium carbonate	20.1
Total	8,300.1

TABLE IV

Production of Elk Basin Field by Years

	Barrels		Barrels
1916	721,000	1923	652,000
1917	1,530,000	1924	432,000
1918	1,067,000	1925	320,000
1919	830,000	1926	288,000
1920	828,000	1927	338,861
1921	755,000		
1922	697,000	Total	8,458,861

FUTURE DEVELOPMENT

The field is practically drilled up in the Second Wall Creek sand, which has been the principal producer; and few more wells will be drilled to it. The First Wall Creek sand has been very erratic and was not commercially productive in many wells. If new areas of good porosity are located, there may be sporadic drilling to the First Wall Creek sand. Only three wells have reached the Dakota sands, so that it may be necessary later to drill more wells to that horizon. This will be especially true if any oil should be found around the gas in the same sand. Deep tests will have to be drilled to test the formations below the Dakota, and new discoveries of light oil, black oil, and gas may be made.

SALT CREEK OIL FIELD, NATRONA COUNTY, WYOMING[1]

ELFRED BECK[2]
Tulsa, Oklahoma

ABSTRACT

The Salt Creek oil field has produced 209,619,275.48 barrels of oil since its discovery in 1889. It ranks as one of the largest oil fields of the world and still produces 50 per cent of the light oil of the Rocky Mountain region. The field has two new producing sands and several deeper horizons that remain untested. The development map of Salt Creek and Teapot domes is posted to October 1, 1928.

A subsurface contour map and cross section show that the relation of oil accumulation to structure is in general accord with the anticlinal theory of accumulation. With the exception of the lower Sundance sands the entire Salt Creek field is producing to capacity. The production curve of the Salt Creek field will continue to show a decline.

INTRODUCTION

The Salt Creek oil field of Wyoming is one of the largest oil fields in the United States. Interest in this remarkable field has been nation-wide. Drilling development in the field has rapidly increased in the past few years to keep pace with the decline of the First and Second Wall Creek sands. This paper is written as a review to present an up-to-date story of developments. It is taken for granted that the reader is familiar with the government publications, the work of Wegemann,[3] Estabrook and Rader,[4] Clapp and Lewis,[5] and Knight and Slossom.[6] These publications, together with data possessed by the geological department of the Producers and Refiners Corporation and information received from the U. S. Geological Survey, have been used in the preparation of the paper. E. W. Rum-

[1] Manuscript received by the editor, January 11, 1929.

[2] Producers and Refiners Corporation, Exchange National Bank Building.

[3] C. H. Wegemann, "The Salt Creek Oil Field, Natrona County," *U. S. Geol. Survey Bull.* 452 (1911), and "The Salt Creek Field, Wyoming," *U.S. Geol. Survey Bull. 670* (1918).

[4] E. L. Estabrook and C. M. Rader, "History of Production of Salt Creek Field, Wyoming," *Amer. Inst. Min. Met. Eng., Petroleum Development and Technology in 1925.*

[5] F. G. Clapp and J. O. Lewis, "Leases upon Naval Oil Reserves," *Senate Document* (1913).

[6] W. C. Knight and E. E. Slossom, "Petroleum of Salt Creek, Wyoming," *Bull. Univ. of Wyoming School of Mines* (1896).

sey compiled and drafted the maps. W. W. Rusk also assisted in collecting data, and R. W. Brown wrote the section relating to oil and water analyses.

LOCATION

The Salt Creek oil field is in T. 38, 39, and 40 N., R. 78 and 79 W., Natrona County, Wyoming. Production extends from the old Shannon pool in Sec. 1, T. 40 N., R. 79 W., to the Mammoth Oil Company's Well No. 101 in Sec. 15, T. 38 N., R. 78 W., a distance of 15 miles. The field covers an area of 25,000 acres. The relation of the Shannon pool, Salt Creek, and Teapot Naval Reserve, are shown in Figure 2. Edgerton, Salt Creek, Lavoye, and Midwest are small towns serving the oil field. The field is reached over a paved road from Casper, a city of about 25,000 people, located on the C. B. & Q. railroad and C. & N. W. railroad. A branch railroad now traverses the field, with its terminus at the town of Salt Creek.

Water supply for field use is obtained from a deep well drilled to the Tensleep sand in Sec. 25, T. 40 N., R. 79 W., from a flowing Tensleep well on Powder River dome about 20 miles northwest of the Midwest post-office, and by pumping through a 6-inch pipe line from Platte River at Casper.

HISTORY OF DEVELOPMENT

Although the presence of oil seeps in this region were known prior to 1880, no attempt was made to commercialize the prospects until 1889, when M. P. Shannon of the Pennsylvania Oil Company drilled a well in Sec. 36, T. 41 N., R. 79 W. The well was located in the valley of Salt Creek, presumably near an oil seep in the district now known as the "Shannon pool."

The oil lands near Salt Creek belonged to the federal government, and development was under the provisions of the Placer Mining Act. Under this law an individual could file a claim for 20 acres, and it was necessary for each claimant to sink a 10-foot hole on his claim the first year, and do $100 worth of assessment work per year thereafter for five years, when a patent would be issued by the U. S. Land Office upon the payment of a nominal fee. Only a small part of the land was ever patented. During the first oil excitement that followed the completion of the Shannon well, there were many claimants who could dig the necessary 10 feet but relatively few persons with sufficient capital to drill wells.

The early workers of the field had many hardships to face. Material and oil had to be hauled by wagons 50 miles over sand hills and bad-land

topography in a desolate waste of arid country. In 1903 the Pennsylvania Oil Company hauled 2,300 barrels of oil to Casper by mule teams, and in 1894 transported 7,019 barrels. This success prompted the Pennsylvania Oil Company to build a 50-barrel refinery in Casper in 1895. During this year two other companies, the Wyoming Lubricating Company and the French Syndicate, entered the field.

In 1903 Joseph H. Lobell became interested in the field, and a few years later he sold a considerable portion of the claims in the field to foreign capitalists. In 1908 Poro, an Italian geologist, located a well for these foreign interests, which came in as a 600-barrel gusher. The foreign interests became involved in legal difficulties, the lands being largely unpatented, and these interests were purchased in 1914 by the Midwest Refining Company, now the dominant company in the field.

During the past ten years the history of Salt Creek field has been largely that of expansion and the finding of deeper sands, as reflected in the production figures and in Figure 1.

STRATIGRAPHY

The surface and subsurface formations of the Salt Creek anticline are enumerated in Table I. The formations above the Shannon sandstone have been measured at the surface, but the characteristics and thicknesses of the underlying rocks have been taken from well-log data.

STRUCTURE

The Salt Creek anticline is on the eastern slope of the Big Horn Mountains and on the western flank of the great Sheridan or Powder River Basin. It is 20 miles long and approximately 5 miles wide. The dip of the rocks ranges from 15° to 29° on the west flank and from 5° to 10° on the east flank. Drilling development and irregularities in the folding, due to faulting, have divided the field into three separate domes: Shannon "dome," Salt Creek dome, and Teapot dome.

The Shannon "dome" is a faulted segment on the axis of the anticline, deriving small quantities of oil from the Shannon sand. The oil from this locality is low in gasoline but is an excellent lubricant. The field is no longer of commercial importance.

The Salt Creek dome is the crest of the anticline and the main producing part of the field. The Shannon sand completely encircles the dome in a prominent serrated escarpment. The fold has approximately 1,600 feet of closure and has 22,000 acres of producing oil land within its limits. It has a large drainage area from the Sheridan Basin, which extends north-

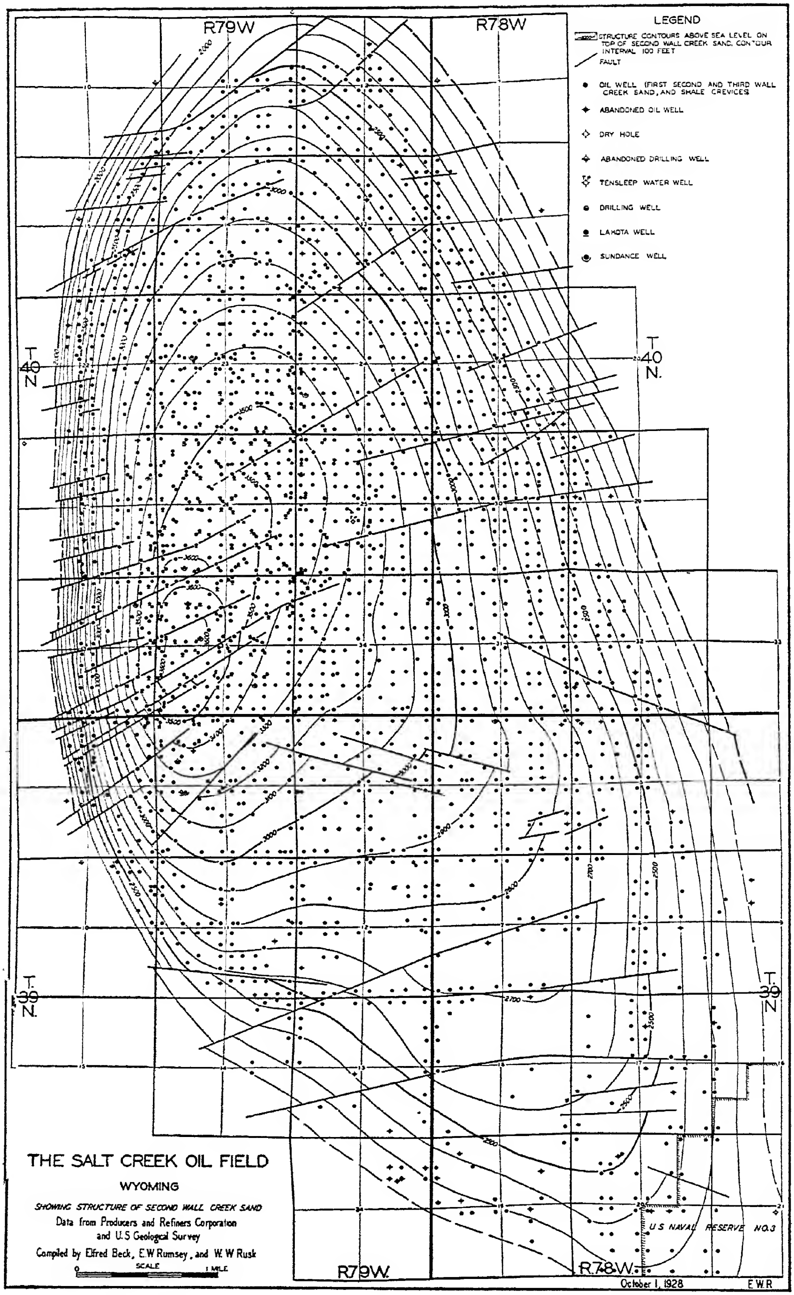

FIG. 1.—Structure of Salt Creek oil field, Natrona County, Wyoming, contoured on top of Second Wall Creek sand. Contour interval, 100 feet. Datum, sea-level.

TABLE I

STRATIGRAPHIC SEQUENCE, SALT CREEK ANTICLINE

Age	Formation		Thickness in Feet	Remarks	No. of Producing Wells
Tertiary	Wasatch		2,500+		
	Fort Union		2,000+		
......?......	Lance		3,200		
	Lewis		1,400		
	Mesaverde		850	Includes Parkman and Teapot sandstone	
	Steele		2,300	Includes Shannon sandstone	
	Niobrara and Carlile shale		1,000		
Cretaceous	Frontier	First Wall Creek sandstone	120	4,350 acres productive	308
		Shale	260		
		Second Wall Creek sandstone	70	22,000 acres productive	1,627
		Shale	165		
		Third Wall Creek sandstone	15	12 acres productive	21
		Shale	270		
	Mowry and Thermopolis		250		
	Dakota group	Muddy sandstone	7		10
		Shale	175		
		Dakota	0–15	10 acres productive	1
		.......*Hiatus*..........			
		Fuson	60		
		Lakota	50	2,135 acres productive	96
	Unconformity				
Jurassic	Morrison		315		
	Sundance		250	2,000 acres productive (est.)	15
Triassic	Chugwater		700		
Permian	Embar		220		
Pennsylvanian	Tensleep		270		1 water well
	Amsden		210	Not penetrated	
Mississippian	Madison		400		

eastward for a distance of 40 miles. The structure presents a type example of epi-anticlinal faulting.[1]

Teapot dome is the southern extension of the Salt Creek dome. It is a plunging anticline limited on the north by a series of transverse faults and as much as 300 feet of reverse folding. This secondary structural feature, like the so-called Shannon "dome," is not a true domal uplift on the Salt Creek anticline. Most of the structural closure has been formed by uplifted fault blocks. Figure 2 illustrates the relation between these several reservoirs.

FAULTING

The faulting on the Salt Creek anticline has been discussed by Irwin,[2] Estabrook,[3] Wegemann,[4] and Lewis and Clapp.[5] Irwin states that there is a genetic and therefore local and contemporaneous relation between the folding and faulting, which is substantiated by the experiments of Link.[6] The faults are normal, with strikes ranging from N. 40° E. to N. 90° E., in general, and fault planes dipping from 60° to 95°. The complicated system of faulting has had an important bearing upon the accumulation and retention of the hydrocarbons. Shale fissures above and below the Frontier sands have yielded large amounts of oil in many parts of the field. On the far eastern edge of Teapot dome a shale well drilled near a fault had an initial production of 8,000 barrels a day. Such wells have a rapid decline but produce oil for a long period. Migration of oil, gas, and water along fault planes is indicated by ozokerite and calcite stringers found at the surface.

DEVELOPMENT

PRODUCING FORMATIONS

The Cretaceous oil sands of the Frontier formation and Dakota group are the most important producing oil horizons. They are locally called the First, Second, and Third Wall Creek, the Muddy, Dakota, and Lakota sands. Three members of the Sundance formation of Jurassic age are

[1] J. S. Irwin, "Faulting in Rocky Mountain Region," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), p. 105.

[2] *Ibid.*

[3] E. L. Estabrook, "Faulting in Wyoming Oil Fields," *ibid.*, Vol. 7 (1923), p. 100.

[4] C. H. Wegemann, *op. cit.*, and "Notes of the Oil Fields of Wyoming," *ibid.*, Vol. 4 (1920), p. 40.

[5] F. G. Clapp, "Leases upon Naval Oil Reserve," *S. Res. 282* and *S. Res. 294* (October 23, 1923), p. 131.

[6] T. A. Link, "The Origin and Significance of Epi-Anticlinal Faults as Revealed by Experiments," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), p. 853.

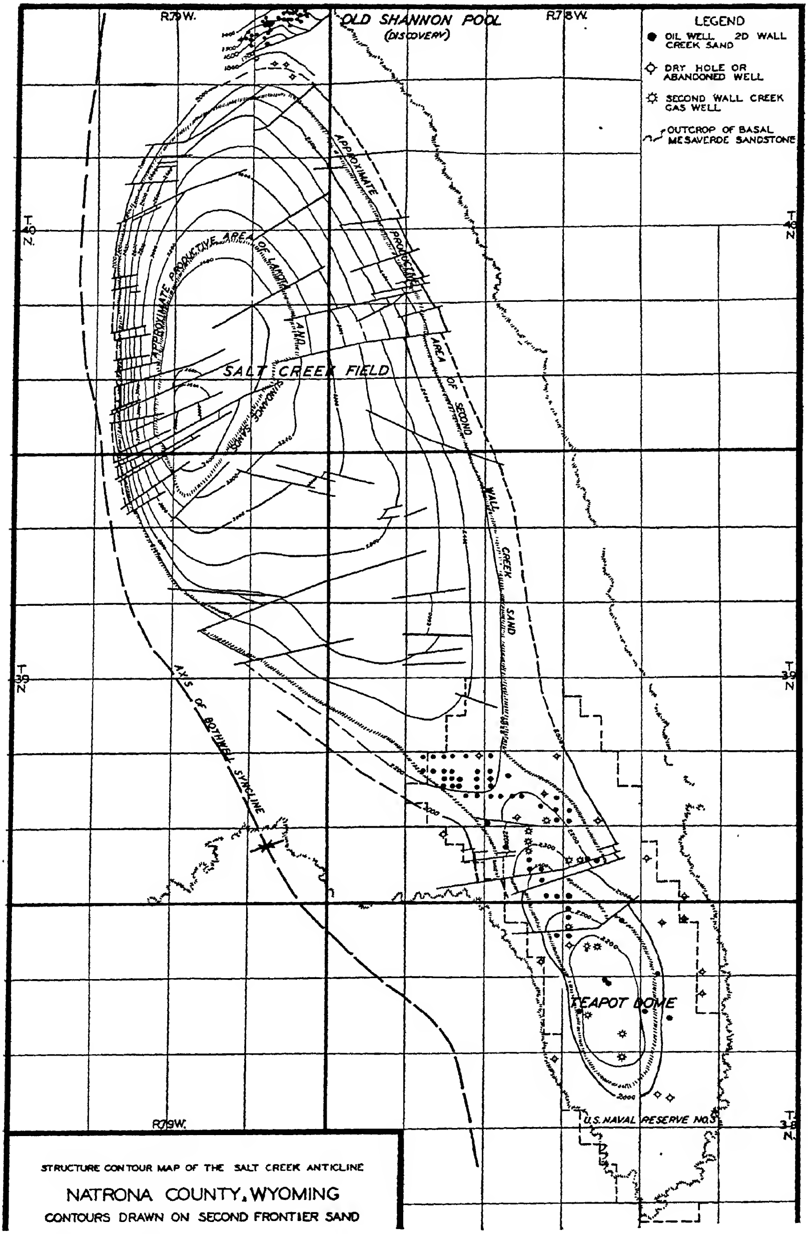

FIG. 2.—Structure of Salt Creek field contoured on second Frontier sand. Contour interval, 200 feet. Datum, sea-level. Width of area mapped, 10 miles. Compiled by Elfred Beck. Drawn by E. W. Rumsey. Data from Producers and Refiners Corporation, U. S. Geological Survey, and F. G. Clapp.

also productive, and the Embar, Tensleep, Amsden, and Madison formations of Carboniferous age have meager possibilities as yet not properly tested. The Shannon sand produces small amounts of oil in the north end of the field, and important quantities of oil are found in shale crevices throughout the district.

First Wall Creek sand.—Approximately 4,350 acres are productive in the First Wall Creek sand on the Salt Creek dome, but on Teapot dome this sand is water-bearing. The sand was found productive 500 feet structurally down from the apex of the dome, but at present water has encroached nearly to the top of the reservoir. It has produced approximately 35,000,000 barrels of oil, equivalent to nearly 5,000 barrels per acre.

Second Wall Creek sand.—This has been the most remarkable oil-producing reservoir in the Rocky Mountain states, in that it was full of oil to the amount of vertical closure, which covered 22,000 acres on Salt Creek dome. On Teapot dome, less than 1,000 acres was oil-bearing, but approximately 1,500 acres produced gas. Approximately 165,000,000 barrels of the production from the field has been credited to the Second sand.

Third Wall Creek sand.—The Third Wall Creek sand is a lenticular sand found 625 feet below the top of the First sand in the south end of the Salt Creek field. The sand has an average thickness of 15 feet and has produced approximately 1,000,000 barrels of oil.

Shale crevices.—Oil is found in shale crevices above the First Wall Creek sand in all parts of the field, also in a large area across the limiting syncline on the west. Shale oil has been found between the First and Second sands, between the Second and Third sands, and below the Third sand. Approximately 9,000 acres of land have produced shale oil on the Salt Creek anticline, and more than 10,000 acres have been productive in the area west of the field. More than 1,000,000 barrels of oil has been derived from shale crevices.

Muddy Sand.—The Muddy sand is the upper member of the Dakota group. It has an average thickness of 7 feet and is productive in ten wells.

Dakota sand.—The Dakota sand is the middle member of the Dakota group, and it ranges in thickness from almost nothing to 15 feet. It has been productive in one well.

Lakota sand.—The Lakota sand is productive under 2,135 acres. The water line varies from 2,300 to 2,350 feet above sea-level, corresponding with the 3,375-foot and 3,425-foot contours on the Second Wall Creek sand. Most of the oil in this sand has been shut in and has only recently been produced.

Sundance sands.—Production in the Sundance formation is undeveloped. The productive area will comprise approximately 2,000 acres. The initial production will probably be less, and the total recovery per acre will be more, than the Lakota, unless a unit operating plan is installed to control the water in the more porous Lakota. There are three productive horizons in the Sundance formation, and the basal member seems to be the most productive zone.

Lower horizons.—The Embar, Tensleep, Amsden, and Madison formations have meager possibilities as yet not tested on the crest of the anticline. The Tensleep sand produced a flowing water well on the east slope of the anticline 300 feet structurally down from the crest. There is a possible productive area of 1,500 acres in these lower horizons, but they are black oil possibilities only.

TABLE II

SUMMARY OF THE STATUS OF WELLS DRILLED ON SALT CREEK ANTICLINE*
(October 1, 1928)

Wells	Formation from Which Producing
308	First Wall Creek sand
1,627	Second Wall Creek sand
21	Third Wall Creek sand
59	Shale crevices
10	Muddy sand
1	Dakota
96	Lakota
15	Sundance sands
10 (water)	Second sand (abandoned)
12 (gas)	Second sand, Teapot
1 (water)	Tensleep sand

* Wells in the Shannon pool are not tabulated.

Figure 3 is an ideal north-south cross section through the Salt Creek field, showing the relative position of the oil-water line in three producing horizons.

PRODUCTION

Until 1912 only minor amounts of oil were produced from the Salt Creek field, as there were no pipeline connections; but with the building of a pipeline in that year, production materially increased. The early production of the field was from shallow sands, the First Wall Creek sand being the most important contributor. This production showed a continuous increase until 1916, when the peak of the shallow sand production

such as those from the Morrison and Dakota, are similar; but others, such as the Tensleep, are quite distinctive.

The analyses of the waters from a given sand vary considerably throughout the field. For example, the First Wall Creek sand near the edge of the field has a concentration of approximately 2,000 parts per million, but near the crest of the structure the concentration is as high as

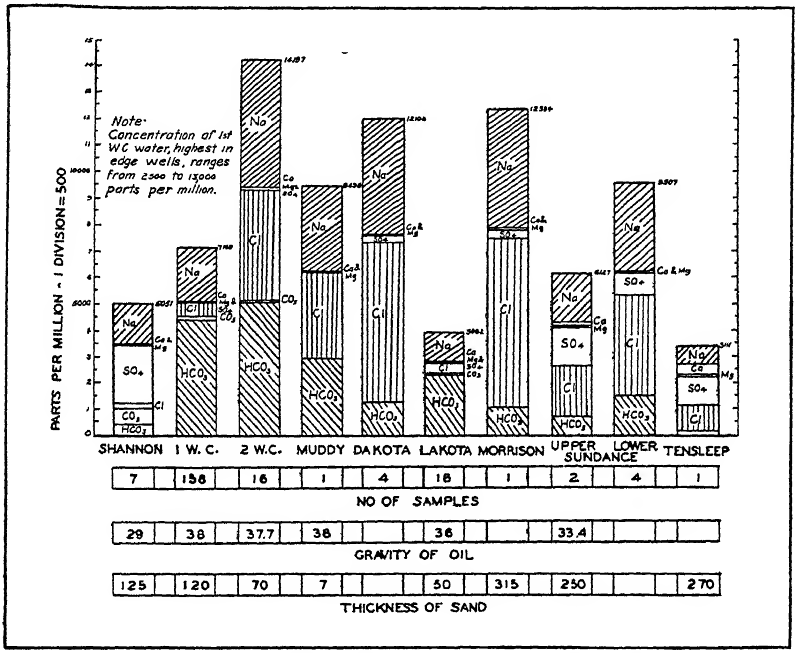

FIG. 3.—Averaged water analyses, Salt Creek field. *W. C.*, Wall Creek. Data from U. S. Geological Survey.

12,000 parts per million. The chlorine content varies from 200 to 500 parts per million near the edge of the field, but is nearly 6,000 parts per million on the crest of the structure. For this reason, when comparing analyses it is necessary to know from what part of the field the water sample has been obtained and to make comparison with waters derived from the same locality.

The influence of the location of the well upon the problem of correlation of oil-field waters is well illustrated by the three analyses shown in Table IV, in which the parts of each radical and of the total solids (T.S.) per million parts of water are indicated.

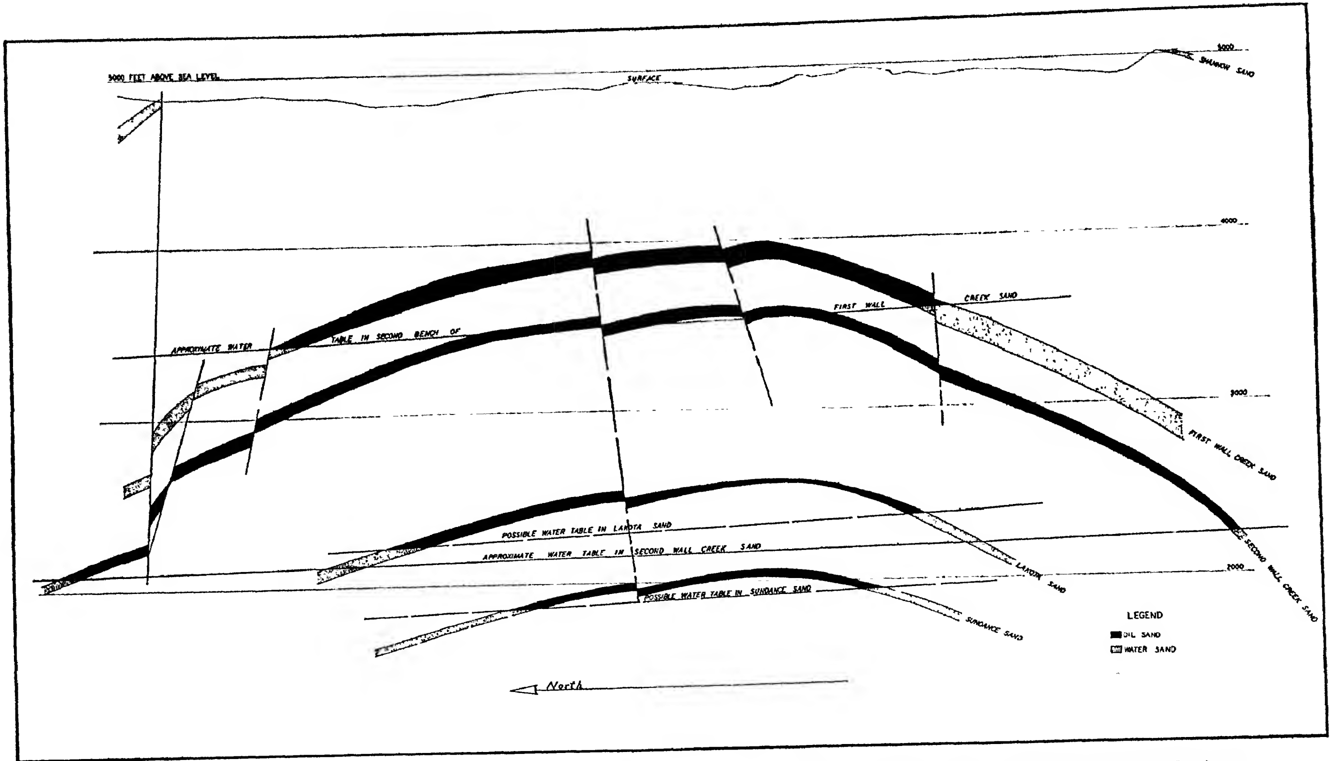

FIG. 4.—Cross section of Salt Creek field, Natrona County, Wyoming, showing relative position of water tables in producing horizons.

According to Ross and Swedenborg, while drilling a well in the NE. ¼, Sec. 19, T. 40 N., R. 78 W., oil appeared with the water, and it was necessary to determine whether this water was derived from the First or Second Wall Creek sand. The water was analyzed, and the analysis is indicated in the second column of Table IV. It will be noticed that this analysis closely resembles the analysis of the water from the First Wall Creek sand obtained from a well in Sec. 35, T. 40 N., R. 79 W., 3 miles distant, but this sample shows an exceptionally high concentration, coming as it does from the crest of the Salt Creek anticline. The analyses indicated in the

TABLE IV*

	First Wall Creek Well 16, SE. ¼, Sec. 35, T. 40 N., R. 79 W.	Second Wall Creek Well 1, NE. ¼, Sec. 19, T. 40 N., R. 78 W.	First Wall Creek Well 1, NW. ¼, Sec. 19, T. 40 N., R. 78 W.
Na	5,321	4,504	1,785
Ca	Trace	Trace	10
Mg	0	0	11
SO_4	0	0	0
Cl	5,940	5,165	345
CO_3	132	Trace	54
HCO_3	3,610	3,060	4,128
TS	11,900	11,900	4,340

* Reprinted by permission from J. S. Ross and E. A. Swedenborg's "Analyses of Waters of the Salt Creek Field Applied to Underground Problems," *Amer. Inst. Min. Met. Eng. Tech. Pub. 157* (1928), p. 12.

second and third columns are of waters from wells less than a mile apart and located on the eastern flank of the dome near the limit of the producing area. Consequently these two analyses are the ones which should be compared; and when this comparison is made, it is obvious that the sample in question did not come from the First Wall Creek sand.

Commonly, and in many widely separated oil fields, the water found in the oil-bearing sands has an exceptionally low sulphate content, the oil having probably reacted chemically upon the water. Such observations may be made in the Salt Creek field. The sulphate content of the chief producing sands, First and Second Wall Creek and the Lakota, is negligible, averaging less than one-half of 1 per cent. Nevertheless, the Shannon sand, which, because of its nearness to the surface might be expected to be in closer connection with meteoric waters and which has produced relatively small amounts of oil, contains water whose average sulphate content is more than 40 per cent. The Tensleep sand, which has not produced oil in the Salt Creek field, contains water having a sulphate content greater than 30 per cent.

OIL ANALYSES

Not only has the oil probably reacted chemically upon the water, but the water has in turn reacted upon the oil. In the Second Wall Creek sand the oil near the edge of the producing area is 6° Bé. heavier than the average oil of the field. But the alteration of the oil extends back less than $\frac{1}{4}$ mile from the edge of the pool, and Estabrook reports that "the alteration of the oil in Salt Creek is apparently limited to a zone extending 100–150 feet structurally above the water line."[1]

TABLE V

ANALYSES OF SALT CREEK AND TEAPOT OILS*

	Crude Oil from			
	Shale†	First Sand‡	Second Sand§	Third Sand‖
Specific gravity	0.810	0.8323	0.835	0.839
A.P.I. gravity	43.2	....	38.0	37.2
Sulphur, per cent	0.12	....	0.16	0.22
Carbon residue or residuum, per cent	4.03	....	5.49	3.6
Approximate summary, per cent:				
Gasoline and naphtha	39.5	29.5	29.9	28.2
Kerosene	17.3	14.5	15.7	4.7
Gas oil	10.6	....	9.9	18.3
Light lubricating distillate	10.8	....	10.6	11.8
Medium lubricating distillate	5.3	....	5.9	8.1

* This table is an abbreviated form of a table compiled by E. L. Estabrook and Clarence M. Rader, based upon analyses by the U. S. Bureau of Mines. For the complete table see "History of Production of Salt Creek Field, Wyoming," *Amer. Inst. Min. Met. Eng., Petroleum Development and Technology in 1925*, p. 236. Printed by permission.

† Shale crevice oil, Teapot dome; well 301-A, SW. $\frac{1}{4}$, Sec. 2, T. 38 N., R. 78 W.; depth 1,520 feet.

‡ First Wall Creek sand, Salt Creek field; well 31, NE. $\frac{1}{4}$, Sec. 26, T. 40 N., R. 79 W.; depth 1,003–82 feet.

§ Second Wall Creek sand, Teapot dome; well 401-A, SE. $\frac{1}{4}$, Sec. 33, T. 39 N., R. 78 W.; depth 3,041 feet.

‖ Third Wall Creek sand, Salt Creek field; well 12, NW. $\frac{1}{4}$, Sec. 20, T. 39 N., R. 78 W.; depth 2,828–43 feet.

Analyses of the oil from some of the more important horizons in the Salt Creek field are indicated in Table V, which shows a relatively light gravity and a relatively high gasoline recovery from the shale oil as compared with the oil from the other horizons.

CASING-HEAD GASOLINE

By the end of 1924, 224,000,000,000 cubic feet of gas had been produced, of which approximately 179,000,000,000, cubic feet has been treated by gasoline plants. The relative amount of gas so treated has

[1] E. L. Estabrook, "Analysis of Wyoming Oil-Field Waters," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 9 (1925), p. 245.

steadily increased from 12 per cent in 1918 to 28 per cent in 1924. During the same period there was at first an increase in the yield of gasoline due to improved methods, followed by a decline as "leaner" gases were treated. The yield of gasoline per 1,000 cubic feet of gas was 2.13 gallons in 1918; 4.66 gallons in 1921, when the maximum yield was obtained; and 1.46 gallons in 1924.

DRILLING AND OPERATING METHODS

Practically all of the drilling is done by cable-tool methods. The depth to the Second Wall Creek sand ranges from 1,400 feet to 2,900 feet. The average drilling time for a 2,000-foot hole is somewhat less than three months, and the cost approximately $20,000.00. Waters from the Shannon sand and the First Wall Creek sand must be shut off in many parts of the field, and cementing is the usual practice.

"Shooting" the wells is highly beneficial, owing to the hardness of the sands, and for one large group of wells resulted in an increase in production from 100 barrels to 500 barrels a day. Wells are pumped both from the beam and from central powers. Electricity is the only form of power used by the Midwest Refining Company in its operations, including pumping and drilling.

Repressuring of the First sand has not been successful. Gas has been applied through "key wells" to the Second sand with very satisfactory results. Repressuring of the Second sand has kept the decline curve for the field above 40,000 barrels. The gas drive has not been tried but would probably not improve the water problem in the Lakota and Sundance sands.

A notable feature connected with the history of development of the Second sand is the fact that the flank wells have a longer life than the wells located high on the structure. Unlike the First sand, water encroachment has not followed the depletion of the reservoir in the Second sand. The high gas ratio of the wells on top of the structure has caused the contents to be emptied quickly, while the lack of included gas and the absence of hydrostatic pressure has held the oil on the perimeter of the fold.

The First and Second sands of the Salt Creek field offer type examples of volumetric and capillary control, respectively, as described by Herold.[1]

[1] S. C. Herold, *Analytical Principles of the Production of Oil, Gas, and Water from Wells* (Stanford University Press, 1928).

LANCE CREEK OIL AND GAS FIELD, NIOBRARA COUNTY, WYOMING[1]

WILSON B. EMERY[2]
Casper, Wyoming

ABSTRACT

Lance Creek oil and gas field, discovered in 1918, is on a large anticline. Structure has controlled the accumulation of oil and gas. Production is from sands of the Dakota group (Cretaceous). The First, or Muddy, sand yields oil in small amount in a limited area on the crest of the fold, but the principal production is from the lower sands of the Dakota group. In these sands, gas in large volume is found throughout a large area, and a very narrow strip of oil territory borders the gas cap on the south and east. Because of steeper dip, the oil-bearing zone in these sands is probably much narrower on the north and west flanks than on the others, and has not yet been found by drilling, though there seems no reason to expect it to be absent. The water table originally plunged eastward, and production was obtained at the east end of the field down as far as the limit of closure, but farther west production was never found so low structurally. The gravity of the oil is 41.8° Bé. The average recovery of gasoline from the natural gas is 1.54 gallons per thousand cubic feet. To January, 1927, the field had produced nearly 3,500,000 barrels of oil.

INTRODUCTION

The Lance Creek oil and gas field is in west-central Niobrara County, Wyoming, about 30 miles from the eastern border of the state. It may be readily reached by good roads from either Manville or Lusk, towns on the C. & N. W. railroad 22 miles south of the field. It can also be reached from Edgemont, South Dakota, on the C. B. & Q. railroad, but the distance from this point is about twice as great as it is from Manville or Lusk.

The producing wells in the field are located in an area of gently rolling topography limited on the north by low bluffs of the Foxhills sandstone (Upper Cretaceous) and on the south by escarpments of White River beds (Tertiary). The average elevation in the field is about 4,400 feet, and the climate is accordingly somewhat more equable than that in other Wyoming fields at higher altitudes. There are no perennial streams in the field, but water commonly stands in pools along the course of Lance

[1] Presented by title before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, June 29, 1928. Published by permission of The Ohio Oil Company.

[2] 1041 S. Center St.

Creek, or, in exceptionally dry years, when such pools dry up, water may always be found at a shallow depth beneath the stream bed.

The discovery well in the field was drilled by The Ohio Oil Company upon the recommendation of C. J. Hares, chief geologist for the company. This well obtained small production from the Wall Creek sand on March 13, 1918. It was subsequently deepened to the Muddy sand and had an initial production of 1,500 barrels per day on October 6, 1918. This well is Well No. 1 in the northwest corner of Sec. 36, T. 35 N., R. 65 W., as shown in Figure 1. Its successful completion by The Ohio Oil Company marked the termination of a five-year period during which other operators had made persistent but unsuccessful attempts to drill wells down to the producing sands.

Several short articles have been published on the Lance Creek field, and in 1920 a comprehensive report by E. T. Hancock[1] was issued by the U. S. Geological Survey. Since the date of Hancock's report, drilling has furnished much further information regarding the geologic structure and the relation of oil and gas accumulation to structure in this field. The present paper and the accompanying map record this later information.

STRATIGRAPHY

The White River formation (Oligocene) crops out extensively in the field, concealing the west end and much of the south flank of the structure. On the north flank the Lance formation (Eocene?) is exposed, and below it the Foxhills sandstone (Upper Cretaceous) forms a prominent line of bluffs which clearly reflect the trend of the fold. The Pierre shale (Upper Cretaceous) forms the surface of the structure between the Foxhills outcrop on the north and the escarpment of the Wind River formation on the south.

Drilling commences in the Pierre shale or in the Wind River formation which unconformably overlies the Pierre. The holes penetrate the Pierre and Niobrara shales and near the base of the Carlile shale encounter a sandy horizon which is equivalent to the Wall Creek sandstone of other Wyoming fields. This horizon is variously reported in the logs at Lance Creek as "sand," "sandy shale," or "shells." On the crest of the dome it lies at a depth of about 1,800 feet. A showing of oil was obtained in the discovery well, and showings have been found in it at other places in the field; but it has not yielded commercial production.

Below this sandy zone the holes again penetrate shale to an average

[1] E. T. Hancock, "The Lance Creek Oil and Gas Fields, Niobrara County, Wyoming," *U. S. Geol. Survey Bull. 716-E* (1920), pp. 91–122.

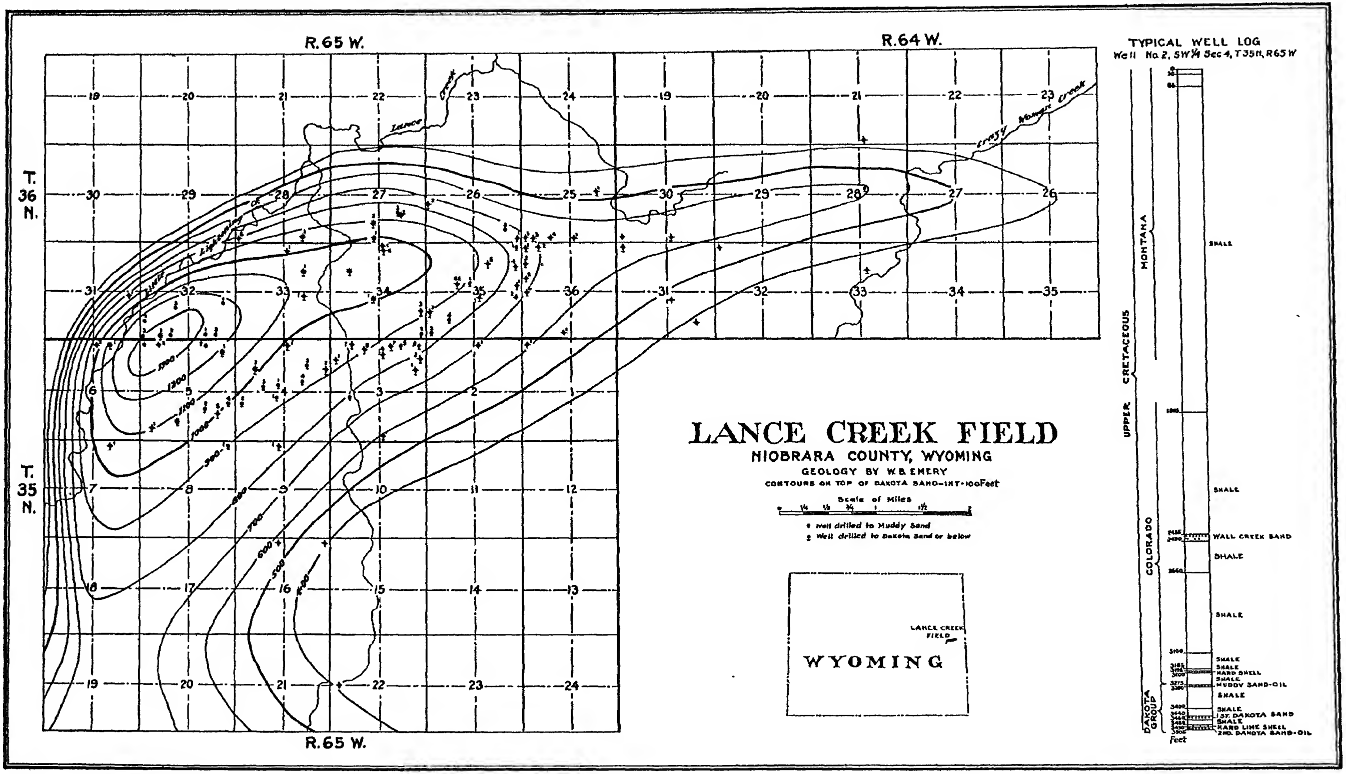
R. 65 W.
R. 64 W.
T. 36 N.
T. 35 N.
R. 65 W.
LANCE CREEK FIELD
NIOBRARA COUNTY, WYOMING
GEOLOGY BY W. B. EMERY
CONTOURS ON TOP OF DAKOTA SAND—INT.—100 Feet
Scale of Miles
Well drilled to Muddy Sand
Well drilled to Dakota Sand or below
LANCE CREEK FIELD
WYOMING
TYPICAL WELL LOG
Well No. 2, SW¼ Sec 4, T 35 N, R 65 W
UPPER CRETACEOUS
MONTANA
COLORADO
DAKOTA GROUP
SHALE
WALL CREEK SAND
SHALE
SHALE
SHALE
SHALE
HARD SHELL
SHALE
MUDDY SAND-OIL
SHALE
SHALE
1ST. DAKOTA SAND
SHALE
HARD LIME SHELL
2ND. DAKOTA SAND-OIL
Feet

Fig. 1

depth of 750 feet, below which they encounter, on the crest of the fold, the Muddy sand of the drillers (Newcastle sand of the U. S. Geological Survey). This sand has an average thickness of 15 feet, and production has been obtained from it in a small area on the very top of the structure; but the sand does not persist in the entire field.

The Dakota group, which yields most of the production at Lance Creek, is separated from the Muddy sand by shale with an average thickness of 150 feet. It consists of two sands generally separated by a shale break. The average thickness of the entire series is about 50 feet, of which 3–20 feet comprise the shale break.

SURFACE STRUCTURE

The Lance Creek anticline lies west of a shallow syncline separating it from the Hartville uplift, which is one of the principal uplifts in Wyoming. The anticlinal axis can be traced from Sec. 29, T. 37 N., R. 63 W., southwest almost to the center of Sec. 25, T. 36 N., R. 64 W., where it turns abruptly westward and extends through Secs. 26, 27, 28, 29, and 30 of this township and into Secs. 36, 35, and 34, T. 36 N., R. 65 W. Beyond Sec. 34, T. 36 N., R. 65 W., the fold is masked by an overlap of the Wind River formation, and the axis cannot be determined from surface exposures, though the outcrop of the Foxhills sandstone on the flank indicates that the trend of the fold changes to a general southwest and south direction beyond this point.

The Lance Creek anticline is asymmetrical, with the steeper flank on the west and northwest. Dips ranging from 15° to 32° are common on this flank. The opposite flank is gently inclined, with prevailing dips ranging from 2° to 4°.

SUBSURFACE STRUCTURE

The subsurface structure is similar to that on the surface. Drilling has shown that the flank on the north and northwest is the steeper, with the sharpest dips located in Sec. 31, T. 36 N., R. 65 W., and Sec. 6, T. 35 N., R. 65 W., opposite the crest of the dome; the south flank of the structure slopes much more gently. The axis plunges at a somewhat greater angle south of the crest than it does toward the east, where it is in effect terraced (Fig. 1). The structure has at least 550 feet of closure in the Dakota sand, with the possibility of 100 feet more, though this cannot be proved.

The folding of the Lance Creek anticline was completed after the deposition of the Lance formation, which is provisionally referred to the Eocene. That the folding is definitely pre-Oligocene is shown by the fact

that the White River formation of Oligocene age unconformably overlies the Lance and all older beds now exposed in the fold but is itself not involved in the folding.

It is the writer's opinion that the Lance Creek anticline originated from lateral compression.

FAULTING

There is no clear-cut evidence of faulting in the field. The datum elevations in the southwest quarter of Sec. 34, T. 36 N., R. 65 W. and adjacent tracts are somewhat discrepant and suggest possible faulting, but, as the differences may be due to the poor character of the logs, the placing of a fault at this location is not soundly justified. It is the writer's opinion that the discrepancies mentioned are due to the impossibility of accurate correlation rather than to faulting, and that there is no faulting in the field.

RESERVOIR ROCKS

Production has been found at five horizons in the Lance Creek field. Of these the highest is the Wall Creek sand, which, though it has given excellent showings of oil, has not been found of commercial value. For that reason it will not be discussed further. The next lower horizon is the Muddy sand, which yields oil in a small area on the crest of the fold. The principal producing zone is the Dakota, composed of two sands. These sands yield only gas within much of the productive area; but below the gas cap, oil in large volume has been encountered in them in a narrow strip of territory on the south and east flanks of the structure.

Muddy sand.—The Muddy sand is well developed over the crest of the dome, where it ranges from 10 to 20 feet in thickness; but it is of variable character elsewhere on the structure. This sand commonly has a cap rock 2 or 3 feet in thickness, and below the cap rock it consists of soft sand layers with interbedded thin harder streaks. The production occurs in the soft sand between the hard layers.

It is thought that the Muddy sand, like the Dakota sands below, was deposited near shore in an encroaching sea. The dark marine shales above and below it are considered the source of the oil now found in it.

Dakota sands.—The upper sand of the Dakota ranges from 15 to 30 feet in thickness and generally in this field has 2 to 5 feet of hard, tightly cemented sandstone at the top, commonly reported by the drillers as a "hard shell." This sand is persistent throughout the field but is broken in the eastern part. In this part of the field the upper bench carries water and the lower bench yields oil. In the early drilling this feature was not rec-

ognized, and several wells drilled into the lower bench with a hole full of water from the upper bench reported the entire sand as water-bearing and were abandoned. Subsequent drilling indicates that if these wells had been properly handled they would have made producers. The early gas wells on the upper part of the structure stopped in this upper sand after finding gas in large volume with high rock pressure.

The lower sand of the Dakota is separated from the upper sand by a shale interval ranging in thickness from 3 to 20 feet. Drilling has shown that it is continuous throughout the field. It is a large producer of oil and gas. Unlike the upper sand, it does not have a cap rock, but oil and gas are held in it by the impervious shale separating it from the sand above.

Both sands of the Dakota are of medium grain, and soft, indicating a favorable percentage of porosity. They were deposited close to shore in an encroaching sea. The oil and gas now contained in them are thought to have originated from the dark shales associated with them.

Lakota sand.—One well on the crest of the Lance Creek structure found gas in large volume in the Lakota sands, but three other wells less favorably located structurally did not develop production from this horizon. On the crest of the dome the Lakota is separated from the base of the Dakota sand by 20 feet of pink shale. Below this shale there is a 20-foot sand, followed downward by a 4-foot shale break, and below this, 18 feet or more of sand. These two sands constitute the Lakota.

In lithologic character and origin the Lakota sands are similar to those of the Dakota above.

RELATION OF ACCUMULATION TO STRUCTURE

The position of gas, oil, and water in the Dakota sands of the Lance Creek field is in accordance with the anticlinal theory of accumulation. Over the crest of the structure is a broad area in which gas only has been encountered in these sands, and bordering this gas cap on the south and east, oil in large volume has been found in a relatively narrow belt. It is probable that this belt originally continued around the structure north and west of the gas cap, but, because of the steeper dip in these directions, it was to be expected that the oil-bearing zone would be found to be much narrower here than on the other flanks, and for this reason it was not located. Decrease of gas pressure on the crest of the dome, due to extraction of the gas and the consequent encroachment of edge water, may have so adversely affected this belt on the north and west flanks of the structure that it is possible no oil may ever be found on it.

If one considers the ideal theoretical distribution of gas, oil, and water

on an anticline to be that in which the gas-oil line and oil-water line parallel the structure contours, then their distribution in the Lance Creek anticline departs greatly from the ideal. In this field both the gas-oil line and the water table plunge toward the northeast, with the result that production of both gas and oil extends much farther down structure in this direction than it does elsewhere on the anticline. Thus gas Well No. 2 in the SW. $\frac{1}{4}$, Sec. 27, T. 36 N., R. 65 W., is almost 200 feet lower structurally than Well No. 1 in the NE. $\frac{1}{4}$, Sec. 6, T. 35 N., R. 65 W., which is the lowest gas well on the west side of the field.

It is worthy of note that originally the Dakota sands contained oil in the east end of the field almost down to the ultimate structural closure, and perhaps even below that closure, whereas at the southwest end of the field oil production did not reach within 200 feet or more of the closing contour. There is not sufficient evidence along the axis south of the crest of the anticline to determine exactly the amount of closure, but it is certain that the 800-foot contour closes. If this contour actually marks the closure, then production at the east end of the field originally extended almost 100 feet below the closure. If, on the other hand, the 700-foot contour closes (and there is no definite information to prove either that it does or that it does not), then oil was present practically down to the closing contour at the east end of the field. Under either condition, the Lance Creek field differs considerably from most Rocky Mountain fields, as commonly in these fields production does not extend down dip more than half the distance from the anticlinal crest to the closing contour.

The plunge of the water table and the gas-oil contact in the Dakota sands of the Lance Creek anticline is away from the trough of the Powder River basin, on the southeast flank of which the fold is located. The plunge roughly parallels that of the Hartville uplift, which limits the Powder River basin on the southeast.

OIL

The oil from the Lance Creek field is green in color and has a sweet odor. Its gravity is 41.8° Bé. The oil as produced has a higher temperature than that from most oils in the Rocky Mountain area, as it ranges from 98° to 105° F. The following analysis is typical for oil from this field.

GAS

The gas wells in the Lance Creek field commonly came in with initial productions ranging from 20,000,000 to 30,000,000 cubic feet per day and had initial rock pressures of more than 900 pounds. By January 1, 1927, the rock pressure had declined to 450 pounds.

TABLE I

KANSAS CITY TESTING LABORATORY FRACTIONAL GRAVITY DISTILLATION ANALYSIS OF PETROLEUM, LANCE CREEK FIELD

Specific gravity..................0.815
Color..........Green 1270 (Iodimetric)
Odor..........................sweet
Degrees, Baumé, U. S.............41.8
Degrees, Baumé, Tag 3...........42.1

Percentage	Temperature Degrees F.	Gravity of Fraction and Equivalent in Degrees Bé.	Gravity of Total over and Equivalent in Degrees Bé.	Gravity of Stream and Equivalent in Degrees Bé.
0	170			
5	198 216	0.702=70.1	0.702=70.1	0.702=70.1 0.712=67.2
10	232 242	0.722=64.5	0.712=67.2	0.722=64.5 0.731=62.1
15	262 278	0.739=60.1	0.721=64.7	0.739=60.1 0.747=57.9
20	289 305	0.754=56.2	0.729=62.6	0.754=56.2 0.760=54.7
25	322 340	0.766=53.2	0.736=60.7	0.766=53.2 0.772=51.8
30	351 377	0.778=50.4	0.743=59.0	0.778=50.4 0.783=49.2
35	387 420	0.789=47.8	0.750=57.2	0.789=47.8 0.795=46.5
40	436 459	0.801=45.1	0.756=55.7	0.801=45.1 0.806=44.1
45	475 493	0.811=43.0	0.762=54.2	0.811=43.0 0.815=42.1
50	515 534	0.819=41.3	0.768=52.8	0.819=41.3 0.823=40.4
55	550 560	0.826=39.8	0.773=51.6	0.826=39.8 0.829=39.2
60	570 604	0.832=38.6	0.778=50.4	0.832=38.6 0.835=38.0
65	Vacuum	0.837=37.6	0.783=49.2	0.837=37.6 0.840=37.0
70	Vacuum	0.844=36.2	0.787=48.3	0.844=36.2 0.847=35.6

Gasoline (58.1° Bé.), per cent.....32.5
Kerosene (42.8° Bé.), per cent....27.5
Gas oil (35.0° Bé.), per cent......20.0
Fuel oil (high in wax), per cent....20.0
Transparency...........Reddish-brown
Cold test........................10° F.
Water...........................None
Sediment, per cent.................2.0

Viscosity in Degrees F.	Saybolt U. S.
40	300
50	145
60	60
70	48
80	42
90	39
100	36

The gas has a sweet odor and is of good quality, free from sulphur. There is considerable variation in the amount of casinghead gasoline it contains, as the yield ranges from .54 to 1.90 gallons per thousand cubic feet. The average extraction per thousand cubic feet is 1.54 gallons.

WATER

As previously stated, the water table in the Dakota sands of the Lance Creek plunges toward the northeast and was originally 200 feet lower at the east end of the field than at the west end. Concurrent with the withdrawal of gas and oil from the sands, the water level has risen, so that it is now more than 100 feet higher in the east end of the field than it was when the field was discovered. It has also encroached on the south side of the field, and the water line is now irregular in this part of the field, owing to water being pulled into older wells from which a large yield of oil has been obtained, though it has not migrated so far upward around later wells that have not yet reached the stage of exhaustion manifested in the older wells.

Though not pure, the water of the Lance Creek field is to be classed as fresh water, as opposed to the salt water so common in many fields outside the Rocky Mountain province.

OIL AND GAS PRODUCTION

As shown earlier in this paper, the Lance Creek anticline is largely concealed by Tertiary deposits, with the result that in advance of drilling exact details of structure were not available. It is therefore interesting that the discovery well, which is Well No. 1, Sec. 36, T. 36 N., R. 65 W., should have had an initial production of 1,500 barrels per day from the Dakota sand, as later development proved it to be almost an edge well. Other large wells were found later, of which the largest was Well No. 2 in the SW. $\frac{1}{4}$, Sec. 4, T. 35 N., R. 65 W., with an initial production of 2,965 barrels.

In the Muddy sand, which is productive only in a small area on the very crest of the anticline, no large production was ever encountered. Wells in this sand commonly had an initial production of about 50 barrels, though the range was from 12 to 162 barrels.

The yearly production of oil in the Lance Creek field has been erratic. In a small productive area with few producing wells, all new wells of large volume have made a marked increase in the production for the year in which they were completed. Because of this variation in production from year to year, a satisfactory decline curve for the field as a whole

cannot be constructed, and no reliable estimate of future production can be made. It seems that possibly 800,000 barrels of oil remain to be produced from the field subsequent to January 1, 1927, from the area already proved productive. Should a productive belt on the north and west flank be located in the future, this figure might be very materially increased. This figure also does not take into account possible production from sands below the present producing horizons which are yet untested.

Table II gives the oil production of the field by years to January 1, 1929.

TABLE II

YEARLY PRODUCTION IN LANCE CREEK FIELD

Year	Production in Barrels
1919	456,457
1920	350,845
1921	347,543
1922	281,450
1923	356,764
1924	736,725
1925	384,160
1926	532,018
1927	264,261
1928	200,872

It is estimated that the gas originally present in the Dakota sand in the Lance Creek field amounted to 43,000,000,000 cubic feet, and that on January 1, 1927, the reserve remaining was 15,000,000,000 cubic feet. Gas is now being withdrawn from the field at the rate of 2,000,000,000 cubic feet yearly for the manufacture of casinghead gasoline and carbon black. Somewhat more than half this amount is passed through the gasoline plant before being consumed in the manufacture of carbon black. A small amount of gas is used in connection with the production and drilling of oil wells.

ROCK RIVER OIL FIELD, CARBON COUNTY, WYOMING[1]

WILSON B. EMERY[2]
Casper, Wyoming

ABSTRACT

Rock River oil field was discovered in May, 1918. The oil comes from the sands of the Dakota group (Cretaceous). Accumulation has been controlled by structure, but the water table plunges nearly 900 feet from the south to the north end of the field. Production holds up better in wells on the flanks of the structure than in wells higher structurally. The gravity of the oil is approximately 37° Bé. Production to date has been more than 10,000,000 barrels, and it is thought that possibly as much more will be produced in the future.

INTRODUCTION

The Rock River oil field in Carbon County, Wyoming, is situated in T. 19 and 20 N., R. 78 W., 10 miles southwest of Rock River station on the main line of the U. P. railroad. It has an average elevation of 7,200 feet and lies close to the western edge of the Laramie Plains, from which the Medicine Bow Mountains rise abruptly 6 miles southwest of the field. The field itself is on gently sloping ground along Rock Creek and its tributaries, which are perennial streams of clear water. On account of its location the area is subject to long and rigorous winters with correspondingly short, though delightfully pleasant, summers.

The discovery well, which is Well No. 1, SW. ¼, Sec. 35, T. 20 N., R. 78 W., was brought in on May 1, 1918, by The Ohio Oil Company, drilling upon the recommendation of C. J. Hares, chief geologist. On January 1, 1927, there were 59 producing wells with a total average daily production of 3,000 barrels.

Figure 1 shows the structure of the Rock River field and the location of the wells. This map is based on one prepared by Hares in 1921 and revised to January 1, 1927, by the writer, from drilling records since 1921.

STRATIGRAPHY

Quaternary gravels and alluvium mask much of the Rock River anticline, and good exposures of the underlying Cretaceous rocks in

[1] Presented by title before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, March 2, 1928. Published by permission of The Ohio Oil Company.

[2] 1041 S. Center St.

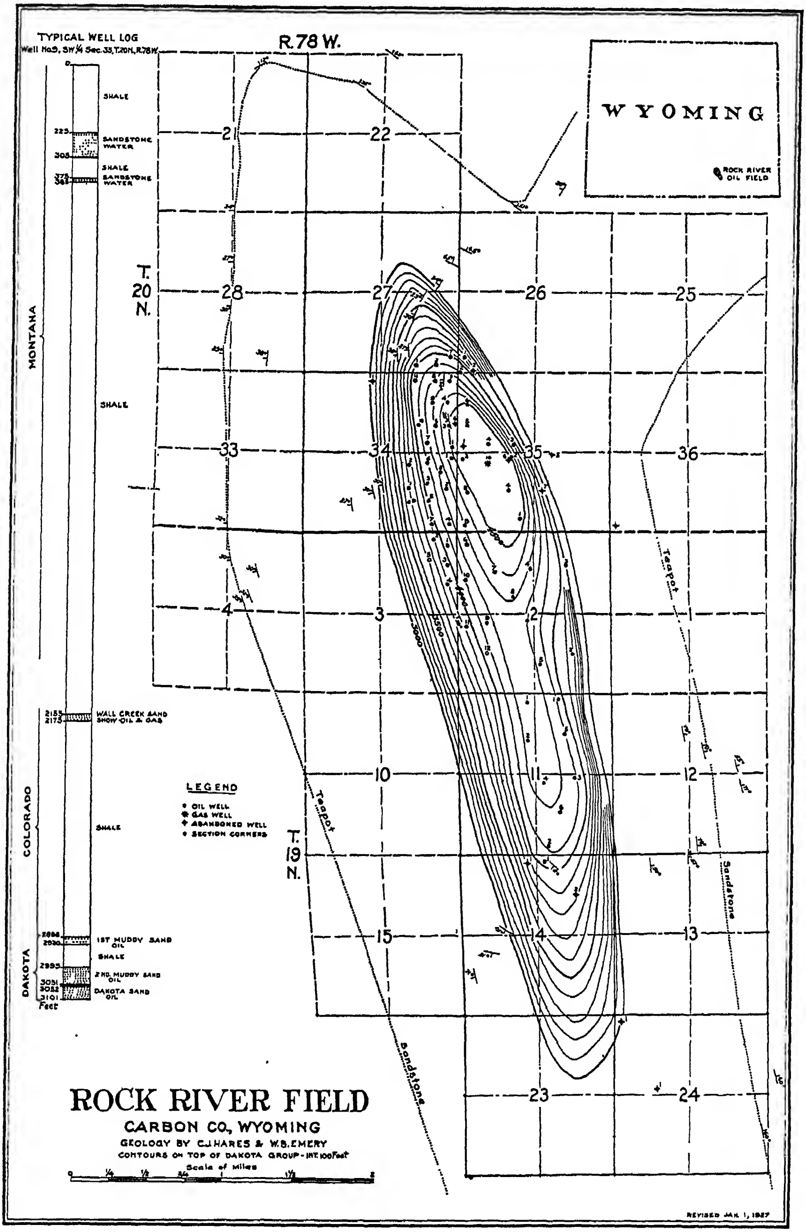
TYPICAL WELL LOG
Well No.5, SW 1/4 Sec.33, T.20N., R.78W.
SHALE
SANDSTONE WATER
SHALE
SANDSTONE WATER
SHALE
WALL CREEK SAND SHOW OIL & GAS
SHALE
1ST MUDDY SAND OIL
SHALE
2ND MUDDY SAND OIL
DAKOTA SAND OIL
Feet
MONTANA
COLORADO
DAKOTA
R.78 W.
WYOMING
ROCK RIVER OIL FIELD
T. 20 N.
T. 19 N.
Teapot
Sandstone
LEGEND
OIL WELL
GAS WELL
ABANDONED WELL
SECTION CORNERS
ROCK RIVER FIELD
CARBON CO., WYOMING
GEOLOGY BY C.J.HARES & W.B.EMERY
CONTOURS ON TOP OF DAKOTA GROUP - INT. 100 Feet
Scale of Miles
REVISED JAN. 1, 1927

FIG. 1

which the folded structure is developed are accordingly rare. Isolated outcrops of the Teapot sandstone at the top of the Mesaverde formation constitute the most definite key horizon and were very helpful in outlining the structure. In the northern part of the area, Mesaverde sands below the Teapot are exposed, and along the creek in Sec. 27, T. 20 N., R. 78 W., exposures which may represent the Shannon sandstone may be seen. There are no good outcrops of rocks older than Shannon(?) on the anticline.

Shale of Montana and Colorado age constitutes by far the larger part of the rock encountered in drilling. The Wall Creek sandstone which occurs in the Colorado is thin in the Rock River fields and in places is absent. It is found at a depth of 2,000 feet or more in the wells and yields showings of oil, but is not commercially productive.

Below the Colorado lies the Dakota group, containing the three sands which yield the oil in this field. These sands are known to the drillers as the First Muddy, the Second Muddy, and the Dakota. They are encountered respectively at depths of 2,505, 2,602, and 2,650 feet or more. The typical well log plotted on the map accompanying this report shows graphically the rock encountered in drilling and the position of the Wall Creek sand and Dakota group in the section.

STRUCTURE

Several anticlines and domes are present along the western border of the Laramie Basin. Of these the Rock River anticline is the northernmost. East and southeast of the anticline lies the deepest part of the Laramie Basin, and toward the north the beds dip into the Foote Creek syncline. On the west there is a deep syncline which separates the fold from the uplift of the Medicine Bow Mountains. On the south, across the shallowest syncline associated with the structure, there is a small dome which has recently been found productive of oil.

An interesting feature of the regional structural relations of the Rock River anticline is that, east of the syncline, through Secs. 26 and 36, T. 20 N., R. 78 W., there is a major fold developed at right angles to the Rock River anticline. This fold trends northeast for several miles, exposing successively older rocks as it continues in that direction. With the Rock River anticline, it marks the structural limits of the Laramie Basin on the north and northwest.

The Rock River anticline is a simple but strongly folded structure trending slightly west of north, and at a greater angle in that direction

north of the crest than south of it. It has 1,600 feet of closure, with the crest located in the north third of the closed area. The fold is asymmetric both along the axis and at right angles to the axis. This asymmetry is especially prominent transverse to the axis, for the east, or basinward, flank dips off precipitously at angles as great as 70°, whereas the west, or mountainward, flank is less steep, with dips ranging from 20° to 35°. This feature is readily apparent on the map, as are also the other details of structure.

There is no evidence of faulting in the Rock River anticline.

The subsurface structure of this fold as determined on the top of the Dakota group shows clearly that the underground axis lies west of the axis as developed in the surface rocks. That is, the axial plane dips away from the more steeply folded, basinward flank.

It is the writer's opinion that this fold was caused by lateral compression. Movement may have started as early as the close of the Cretaceous, but certainly was not fully completed until late Eocene time, as the Wasatch formation (Eocene) is involved in the folding.

RESERVOIR ROCKS

The production of the Rock River field comes from the Dakota group, which contains three sands separated by shale. The sands, as well as the interbedded shales, are variable in thickness throughout the field. The uppermost sand, or First Muddy sand of the drillers, shows an average thickness of about 55 feet, and over the crest of the anticline is separated from the next lower, or Second Muddy sand, by about 75 feet of dark shale. The Second Muddy is thinner than the other sands, having an average thickness of only 15 feet. The shale between it and the Dakota sand below has a maximum thickness of 45 feet, but in places it is so thin that careful examination of the drill cuttings is necessary to determine its presence. This is especially true on the west flank of the anticline. On this flank, too, the interval between the First and Second Muddy sands is much less than it is on the crest. Except in Well No. 10, NW. $\frac{1}{4}$, Sec. 2, T. 19 N., R. 78 W., in which the First Muddy is absent, all the wells yet drilled to the base of the Dakota group have found all three sands.

The first two sands are medium-grained, but the Dakota sand is somewhat coarser and in places conglomeratic. Though of variable thickness, they maintain their texture uniformly throughout the field; but they are less indurated on the crest than at other places on the anticline. All the sands are composed of clean quartz grains. The color of the First

and Second Muddy sands ranges from gray to brown; the Dakota sand is light gray to white in color and is in marked contrast with the upper sands.

The First Muddy sand and the Dakota have been found in places to be overlain by a cap rock ranging from 1 to 4 feet in thickness. A cap rock, however, is uncommon in this field, the wells ordinarily drilling from shale directly into the pay sand. No cap rock has been found above the Second Muddy sand in any of the wells.

It is the writer's opinion that the source of the oil now found in the sands of the Dakota group in this field was probably the dark shales associated with these sands.

Lee[1] states that the Dakota "group as a whole is interpreted as the result of accumulation of sediments near the strand line of the advancing Cretaceous sea." In the Rock River field this conclusion is attested by the marine shales included in the group, and the texture and variability of the thickness of the sands also indicate near-shore deposition.

RELATION OF ACCUMULATION OF OIL AND GAS TO STRUCTURE

The arrangement of gas, oil, and water in the Rock River anticline is in accord with the anticlinal theory of accumulation. Though there is a good volume of gas associated with the oil, only a single gas well has been drilled. This well, No. 10 in the SW. ¼, Sec. 35, T. 20 N., R. 78 W., is structurally the highest well in the field and demonstrates the presence of a small gas area on the very crest of the fold. It had an initial volume of nearly 15,000,000 cubic feet of gas with a rock pressure of 250 pounds, and also yielded oil to the extent of 100 barrels a day. The gas is mainly from the Dakota sand, with smaller amounts from the First and Second Muddy sands. This well was not drilled until four years after the field came into production. One wonders whether it might not have been an oil well rather than a gas well had it been drilled earlier, for it is now known that as oil production decreases in wells on the upper part of the dome the gas-oil ratio increases. In fact, this ratio has increased to such an extent that it has become necessary to shut in some of the wells on the upper part of the structure in order to conserve gas pressure in the field as a whole.

There is no water with the oil in any of the sands, but water is present in all the sands structurally below the oil body. Although the water line

[1] Willis T. Lee, "Continuity of Some Oil-Bearing Sands of Colorado and Wyoming," *U. S. Geol. Survey Bull.* 751-*A* (1923), p. 6.

has not been determined for much of the field, drilling shows that there is a very marked plunge of the water table toward the northwest, especially in the First Muddy sand.

At the south end of the field, Well No. 2 in the NE. ¼, Sec. 14, T. 19 N., R. 78 W., found water in the Dakota group at approximately the 3,800-foot contour, while Well No. 1 in the NW. ¼, Sec. 34, T. 20 N., R. 78 W., recently completed, found production in the First Muddy sand at approximately the 3,050-foot contour. Thus the water table in the First Muddy sand plunges about 750 feet in a distance of 3½ miles. That the water table plunges less steeply in the lower sands is shown by the fact that Well No. 1 in the NW. ¼, Sec. 34, T. 20 N., R. 78 W., found water in these sands. The exact limit of production has not yet been determined for the north end of the field in the Second Muddy and Dakota sands, but it is known that in these sands the water table dips at least 150 feet northwest, for Well No. 9 in the SW. ¼, SE. ¼, Sec. 34, T. 20 N., R. 78 W., obtained production in both these sands, whereas at the south end of the field the water line was originally between Well No. 1 in the northeast quarter and Well No. 1 in the northwest quarter of Sec. 14, T. 19 N., R. 78 W.

OIL

The oil of this field is brownish-green in color, with a specific gravity ranging from 34° to 37.1° Bé. It has a sweet odor, and its temperature at the mouth of the well is 72° F.

The higher-gravity oil is found on the upper part of the anticline, whereas the oil from wells down the west flank is of lower gravity. There is also a slight variation in the gravity from the different sands, but neither this difference nor that just mentioned in connection with structural location is sufficient to necessitate producing the sands or the flank wells separately.

Table I shows a typical analysis of the Rock River oil by fractional-gravity distillation. The sample was taken from Well No. 2, SW. ¼, Sec. 34, T. 20 N., R. 78 W.

GAS

Gas is present in the oil in considerable volume, but only one well in the field was predominantly a gas well. This well, No. 10 in the SW. ¼, Sec. 35, T. 20 N., R. 78 W., is located close to the highest point on the structure. It had an initial volume of 14,906,000 cubic feet, with a rock pressure of 250 pounds.

The gas produced with the oil is run through a gasoline plant, and

TABLE I

Analyses of Rock River Oil

Color.......Brownish-green
Specific gravity.......0.838
Degrees Bé.,—U. S......37.1

Percentage	Temperature Degrees F.	Gravity of Fraction and Equivalent in Degrees Bé.	Gravity of Total Over and Equivalent in Degrees Bé.	Gravity of Stream and Equivalent in Degrees Bé.
0	96			
5	166 194	0.680=76.6	0.680=76.6	0.680=76.6 0.698=71.2
10	213 232	0.716=66.1	0.698=71.2	0.716=66.1 0.731=62.1
15	264 270	0.746=58.2	0.714=66.7	0.746=58.2 0.755=55.9
20	310 322	0.764=53.7	0.726=63.4	0.764=53.7 0.772=51.8
25	357 374	0.781=49.7	0.737=60.5	0.781=49.7 0.789=47.8
30	398 426	0.797=46.0	0.747=57.9	0.797=46.0 0.805=44.3
35	457 480	0.813=42.6	0.756=55.7	0.813=42.6 0.819=41.3
40	492 516	0.825=40.0	0.765=53.5	0.825=40.0 0.830=39.0
45	534 566	0.835=38.0	0.773=51.5	0.835=38.0 0.839=37.2
50	582 590	0.844=36.2	0.780=49.9	0.844=36.2 0.845=36.0
55	Gas	0.846=35.8	0.786=48.5	0.846=35.8 0.848=35.4
60	....	0.849=35.2	0.791=47.4	0.849=35.2 0.852=34.6
65	....	0.856=33.8	0.796=46.3	0.856=33.8 0.858=33.4
70	....	0.861=32.8	0.801=45.1	0.861=32.8 0.871=31.0
75	....	0.880=29.3	0.806=44.1	0.880=29.3 0.883=28.8

Gasoline (57.9° Bé.), per cent......30.0
Kerosene (40.2° Bé.), per cent.... 15.0
Gas oil (35.7° Bé.), per cent...... 15.0
Fuel oil, per cent................ 40.0

Cold test................Below −4° F.
Transparency..........Brownish-yellow
Odor..........................Sweet
Sediment, per cent.............. 1.5
Water........................None

Viscosity Degrees F.	Saybolt Universal
20	...
30	...
40	280
50	85
60	62
70	52
80	48
90	46
100	44

the dry gas remaining is then used in the field operations. The gasoline content of this gas averages 0.9566 gallon per thousand cubic feet.

WATER

There is no water in the oil from the Rock River field except at the extreme south end of the field. The water line has not been determined for the first sand, but that the productive area in this sand is larger than that of the lower sands is demonstrated by production from it in Well No. 1, NW. $\frac{1}{4}$, Sec. 34, T. 20 N., R. 78 W., whereas the lower sands in this well showed water.

Well No. 1, NE. $\frac{1}{4}$, Sec. 14, T. 19 N., R. 78 W., was completed in April, 1919, and showed no water, though subsequent drilling proved it an edge well. Water first began to show in this well in May, 1920. It has gradually increased in volume until on January 1, 1927, the well was producing only two barrels of oil daily, accompanied by a large amount of water.

Well No. 2 in the SE. $\frac{1}{4}$, Sec. 11, T. 19 N., R. 78 W., an offset to the well just described, was completed in November, 1923. Two years later

TABLE II

YEARLY PRODUCTION IN ROCK RIVER FIELD

Year	Barrels
1918	10,111
1919	297,936
1920	1,513,329
1921	1,728,039
1922	1,758,617
1923	1,479,501
1924	1,210,235
1925	1,121,576
1926	1,020,900
1927	971,729
1928	921,622
Total	11,026,631

water began to come in with the production. Well No. 6 in the same quarter-section as Well No. 2, just mentioned, when completed in October, 1925, showed some water from the Dakota sands; but at that time the migration of water up the dip had not affected the First and Second Muddy sands so far north, nor has it affected them to date.

The plunge of the water table toward the northwest across the Rock River field has been discussed on a previous page.

PRODUCTION

To January 1, 1929, the Rock River field has produced slightly more than 11,000,000 barrels of oil. The production by years is given in Table II.

It is estimated from the decline curve of the field that the future production will amount to 7,000,000 barrels and that this production will extend through a period of eighteen years before the economic limit is reached. This estimate takes into consideration the fact that since 1923 the decline has been much slower than a curve constructed from production prior to that time would indicate, but does not make any allowance for possible increase in the amount of recovery should production technique be further perfected during the life of the field.

GRASS CREEK DOME, HOT SPRINGS COUNTY, WYOMING[1]

THOMAS S. HARRISON[2]
Denver, Colorado

ABSTRACT

The Grass Creek domal structure is one of the most important of Rocky Mountain fields. It has several producing horizons of both paraffin and asphaltic oils. These are briefly discussed. Maps show the structure development at several periods including Tensleep and Embar (Pennsylvanian), and pre-Jurassic and Frontier (Cretaceous). No theoretical discussion is included.

INTRODUCTION

Grass Creek as a producer of oil ranks only second to Salt Creek among Rocky Mountain fields. It is located within the southwestern part of Big Horn Basin, in Hot Springs County, Wyoming.

The Big Horn Basin is an intermontane geosyncline with the Big Horn Mountains on the east, the Owl Creeks on the south, and the Absaroka Range on the west. Lawson[3] says that the basin forms a part of the Great Laramide trough.

Commercial, light-paraffin, 44°-gravity oil was discovered in the Frontier (Upper Cretaceous) sand in June, 1914. The early development was confined to this sand series. In 1922 a well encountered within the Embar-Tensleep (Pennsylvanian) a heavy asphaltic 22°-gravity oil. Since that time twelve wells have been drilled, though the oil is not now being produced.

GEOLOGY

The geology of Grass Creek has been described by Hintze[4] and by Hewitt.[5] The writer will endeavor to avoid duplication by describing

[1] Presented by title before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, June 21, 1928.

[2] Petroleum geologist, 705 First National Bank Building.

[3] A. C. Lawson, "Folded Mountains and Isostasy," *Bull. Geol. Soc. Amer.*, Vol. 38, No. 1 (March, 1927).

[4] F. F. Hintze, Jr., "The Grass Creek Oil and Gas Field," *Wyoming State Bull. 11*, Pt. 11.

[5] D. F. Hewitt, "Geology and Oil and Coal Resources of the Oregon Basin, Meeteetse and Grass Creek Quadrangles, Wyoming," *U. S. Geol. Survey Prof. Paper 145* (1926).

only the more recent deep-sand development and by limiting this paper strictly to an exposition of the facts presented by recent activity.

Several writers have described the region in general. A few of these not otherwise referred to are listed.[1]

STRATIGRAPHY

The stratigraphy of the Big Horn Basin is described in Table I.

Upper Cretaceous rocks occupy the surface at Grass Creek. Niobrara shales are at the crest, upper Niobrara and Pierre are on the flanks, and the whole is bounded in high escarpment by the Eagle, a basal sandstone coal-bearing member of the Mesaverde.

PRODUCTIVE HORIZONS

Frontier.—At the crest of the dome the first Frontièr sand has been encountered at a depth of 315 feet. There are nine producing sands. The series is the important producer of light oil in several of the more important Wyoming fields.[2] The Frontier oil probably originated in the organic marine Benton shales of which the series forms a part.

Muddy.—The Muddy sand is so named because of its muddy character where first recognized at Greybull Field, Wyoming. It occurs within the Thermopolis approximately 250 feet above the base, but it is not continuous in extent. In several of the Grass Creek wells gas was found in it. The sand is an oil producer in several fields farther south within the Rocky Mountain area.[3]

Dakota.—The Dakota sand also produces gas at Grass Creek, though it has not the prominent character generally exhibited. The sand occurs most persistently in west-central United States. It forms the base of the Upper Cretaceous.[4]

[1] G. H. Eldridge, "Reconnaissance in Central Wyoming," *U. S. Geol. Survey Bull. 119* (1894); N. H. Darton, "Geology of the Bighorn Mountains," *U. S. Geol. Survey Prof. Paper 51* (1906); C. A. Fisher, "Geology of the Bighorn Basin," *ibid., No. 53* (1906); N. H. Darton, "Geology of the Owl Creek Mountains," *59th Congress, 1st Session, Sen. Doc. 219;* D. F. Hewitt and C. T. Lupton, "Anticlines in the Southern Part of the Bighorn Basin, Wyoming," *U. S. Geol. Survey Bull. 656* (1917).

[2] The Frontier sand series is productive of oil in two sands at Elk Basin, two to three sands in Salt Creek, in several sands at Lost Soldier, and at Big Muddy—all in Wyoming. The sand series produces gas at the two Little Buffalo Basin domes 15 miles northwest from Grass Creek.

[3] The Muddy produces gas at Oregon Basin and oil at Lance Creek, Lost Soldier, Rock River, and Rex dome in Wyoming. It is the productive horizon of the Fort Collins and Wellington domes in Colorado.

[4] The Dakota produces gas at Oregon Basin, at Byron, and Elk Basin. It produces light oil at Greybull, where it is known as the Greybull sand; also at Salt Creek, Big

Lakota.—The Lakota sand, 100 feet below the Dakota, although not productive at Grass Creek, is highly productive in many parts of this region. It is ordinarily coarse to conglomeratic and as such is a very favorable reservoir.[1]

Morrison.—The Morrison series, which immediately underlies the Dakota-Lakota (Cloverly) series, has not generally been found productive in Wyoming fields. Several of the Grass Creek tests, however, have shown commercial black oil in one of the sands. The oil has not hitherto been produced.[2]

Sundance.—The Sundance (Jurassic) marine series which underlies the Morrison has not shown commercial oil at Grass Creek. It is productive elsewhere in the Rocky Mountains.[3]

Chugwater.—The Chugwater red beds (Jura-Trias), because of their character, have not generally been considered to offer favorable oil prospects. Several of the lower Chugwater sands in Grass Creek, however, have shown commercial black oil.[4]

Embar.—The Embar is not only productive of black oil at Grass Creek but is a very well-known producer within the region[5] (Fig. 1).

Attention should be directed to the fact that Grass Creek lies in a belt within which the Embar-Tensleep oil prospects are particularly favorable.[6] It is limited southward at present by the Rattlesnake Moun-

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Muddy, Lost Soldier, Lance Creek, Rock River, and Rex dome, Wyoming. It is the oil-producing sand at Cat Creek, Montana, and at Hogback, Rattlesnake, and Table Mesa in northwest New Mexico. It occupies the position of the Woodbine of central Texas.

[1] The Lakota is productive of light oil at Lance Creek, Mule Creek, Salt Creek, Rock River, Rex dome, and Lost Soldier—all in Wyoming.

[2] Morrison light oil is being developed at Iles dome, northwestern Colorado.

[3] Sundance production has been developed on the crest of the dome at Salt Creek, Wyoming. The Ellis of Sweet Grass arch, Montana, occupies its approximate position.

[4] At Hamilton dome, 25 miles south of Grass Creek, several wells produce from a Chugwater sand.

[5] The Embar-Tensleep produces black oil at Oregon Basin, at North and South Sunshine, at Hamilton, Warm Springs, and Black Mountain—all within the Big Horn Basin, Wyoming. South of the Owl Creek Mountains there are such productive structures as Maverick Springs, Circle, Big Popo Agie, Dallas, Twin Creek, Notches, Emigrant Gap, and Poison Spider. The Embar with the succeeding Tensleep and Amsden are the sole representatives of the Pennsylvanian series of Wyoming. The Hermosan of southeastern Colorado and southwestern Utah are Pennsylvanian. The upper.Hermosan of southeastern Colorado and southwestern Utah are Pennsylvanian. The upper Hermosan contains light oil at San Juan, Utah.

[6] John G. Bartram, "Occurrence of Black Oil in Wyoming," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10, Pt. 1 (1926), pp. 443–48.

TABLE I

STRATIGRAPHY, GRASS CREEK, WYOMING

System	Formation			Thickness in Feet	Character of Formations
Quaternary	Alluvium+ Terrace gravels			0–50	Gravel and boulders
Tertiary	Wasatch			3,000±	Red and drab clay; buff and white sandstone with gravel lenses. Bad-land topography
	Unconformity				
	Fort Union (Eocene)				Buff and gray gritty sandstone with drab, red, and green clay conglomerate in lower part and lenticular beds of coal
	Unconformity				
	Lance (Ilo)			900±	Buff and drab sandstone with drab and green clay; no coal. Saurian bones and fresh-water invertebrate fossils
Cretaceous	Montana	Mesaverde	Meeteetse	1,000±	Dark and light gray alternating shales and shaly sandstone, with lenticular beds of lignitic coal
			Eagle	600±	Hard gray and brown massive sandstone alternating with thin-bedded shaly sandstone locally coal-bearing. Forms high prominent scarp around Grass Creek basin. Non-marine
		Cody	Pierre	1,600±	Light gray and light brown sandy shales and massive layers of sandstone near top. (Transitional.) Softer and darker shales in lower part with zones of brown sandy shales. Fossils throughout. Marine
	Colorado		Niobrara	1,000±	Soft black adobe shale with large lime concretions with fossils. Streaks of hard red calcareous shale (marl) near top. Occupies crest of Grass Creek fold. Marine
		Benton	Carlile	300±	Dark shale with several beds of concretions 3 feet in diameter containing fossils. Marine
			Frontier	450±*	Several heavy buff and brown beds of sandstone, ordinarily coarse, with interbedded shales and bentonite. Nine sands productive of oil in Grass Creek. Chief light-oil-producing horizon in Wyoming. Marine
			Mowry		Hard gray shale containing fish scales and thin layers of hard fine calcareous sandstone. Believed by many the source of Frontier oil. Marine

		Thermopolis (contains Muddy)	900±	Gray to black shale with non-persistent sand 250 feet above base (Muddy sand) which produces some gas at Grass Creek. Basal member: 50–75 feet thin-bedded rusty resistant sand and black shale ("Rusty beds"). Marine
	Cloverly	Dakota (Graybull)	30±	Gray coarse sandstone. Not productive in Grass Creek though important producer of gas or oil in several Rocky Mountain fields. Non-marine
Lower Cretaceous?	Cloverly	Fuson	100±	Gray, green, or maroon shales. Non-marine
Lower Cretaceous?	Cloverly	Lakota	80±	Coarse to pebbly massive sand. Not productive at Grass Creek though an important producer of oil in several Rocky Mountain fields. Non-marine
Lower Cretaceous?	Morrison		200±	Purple, red, and gray clays and shales with gray and white coarse, commonly pebbly interbedded sands. Several wells in Grass Creek produced black oil in Morrison
Jurassic	Sundance		300±	Greenish shales and gray sandstone, with thin layers of greenish limestone interbedded. Marine
Jurassic? / Triassic	Chugwater (Red-beds)		1,100–1,200	"Red-beds," red sandstone, clay, and shale with thick bed of gypsum near top. Several beds of limestone, mostly thin. Lower sands often contain oil at Grass Creek. Non-marine
Carboniferous	Pennsylvanian	Embar	47–283	Gray limestone. Some logs show two members interbedded with gray and dark sandstone and shale. The upper lime member is persistent. Important oil producer in Grass Creek and other Rocky Mountain fields
		Unconformity		
Carboniferous	Pennsylvanian	Tensleep	291 upward	Gray massive sandstone, in part calcareous with thin limestone lentils. Important oil producer in Grass Creek and other Rocky Mountain fields
		Unconformity		
Carboniferous	Pennsylvanian	Amsden	65–100	Largely red limestone with thin red shale and sandstone
Carboniferous	Mississippian	Madison	600–1,000	Gray massive limestone
Ordovician	Big Horn		150–300	Siliceous gray limestone. Very hard and massive
Cambrian	Deadwood		700–900	Sandstone shale conglomerate and limestone
Pre-Cambrian†	?			

* Thickness of Frontier beds to and including Tensleep taken from well logs. Other thicknesses from various sources.

† Pre-Cambrian rocks ordinarily at exposure are of granite or schist.

tains and westward by the Wind River and Absaroka Ranges. It also includes the southeastern part of the Big Horn Basin. Although much drilling has been done on the eastern side of the basin, no important development has resulted—this although favorable prospects are suggested by exposed saturations at many localities of Embar-Tensleep exposure.

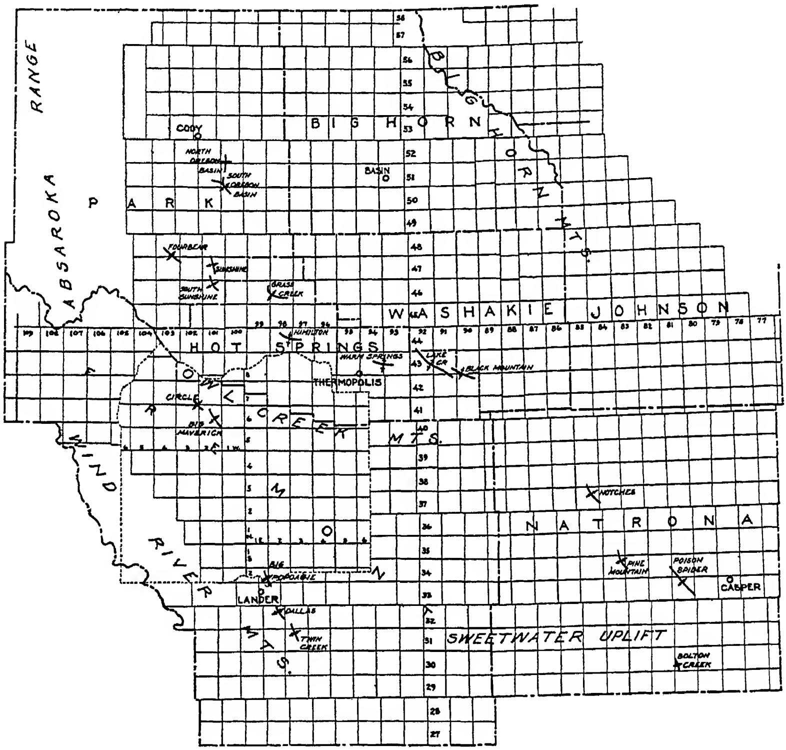

FIG. 1.—Productive Embar-Tensleep fields in central Wyoming. Width of area mapped, approximately 34 townships or 204 miles.

Embar-Tensleep oil probably originated within the Embar. In this region it is made up of marine limestone and calcareous shale rich in organic matter. It is suggested that beyond these confines the Embar either loses its favorable character (the limestones grade abruptly into red beds which are poor source rocks for oil) or that the formation has been eroded.

Tensleep.—The Tensleep sand[1] underlies the Embar, and with it is

[1] See preceding paragraphs on the Embar.

an important producer of black oil. Because of its character, being a sand in contrast to the Embar which is largely lime, the Tensleep is probably the more important producer.

Amsden.—Although the writer is informed that the Amsden "shows" commercial oil at Grass Creek, only three wells have penetrated it. He knows of no other locality where the Amsden has been found productive.

Madison.—The Madison underlies the Amsden (three wells reached its top). The Madison (Mississippian) is at the exposure an unbroken lime series. The writer knows of no commercial oil being developed within it. However, at Sheep Mountain anticline, eastern Big Horn Basin, within Big Horn Canyon, Madison lime is exposed and oil may be seen seeping from the joints. The Union Oil Company of California also reported a small amount of Madison oil in a test in the Hale dome near Thermopolis in southern Big Horn Basin.

STRUCTURE

Twelve wells have reached the Embar-Tensleep horizon. Of these, two, well below the crest, were non-productive in the Embar. Although these serve to show to some extent the limits of the field, the productive area has not been fully outlined.

Because of the present small number of wells drilled, the structures shown will doubtless in the future be subject to some modification. In general, however, because the wells are fairly well distributed, it is the writer's judgment that the information may be accepted.

Amsden.—Only three wells have penetrated the Amsden. They are the L. G. Phelps No. 10, L. U. Sheep No. 13, and State Land No. 39 (Fig. 2). Of these, the two former are reported to have reached the Madison. Evidently these two wells occupied positions on a "high" existing both at the end of Madison and of Amsden time, inasmuch as adjacent wells[1] penetrated a larger series of Tensleep without encountering Amsden. It is suggested that the folding may date back to pre-Cambrian time.

Tensleep.—Fig. 3 shows the structure at the end of Tensleep. Notice that a small thickness of Embar was deposited at the crest with a relatively thick series of strata upon the flanks existing at that time. In four wells the thickness of the Embar ranges from 47 to 80 feet, and in adjacent wells the thickness ranges from 175 to 283 feet. It will also be noticed that the upper limestone (the Phosphora member) of the overlying Embar

[1] Meeteetse 15 No. 19-A, Meeteetse 15 No. 20-A, Meeteetse 17 No. 16, State No. 41, and State No. 42 (Fig. 2).

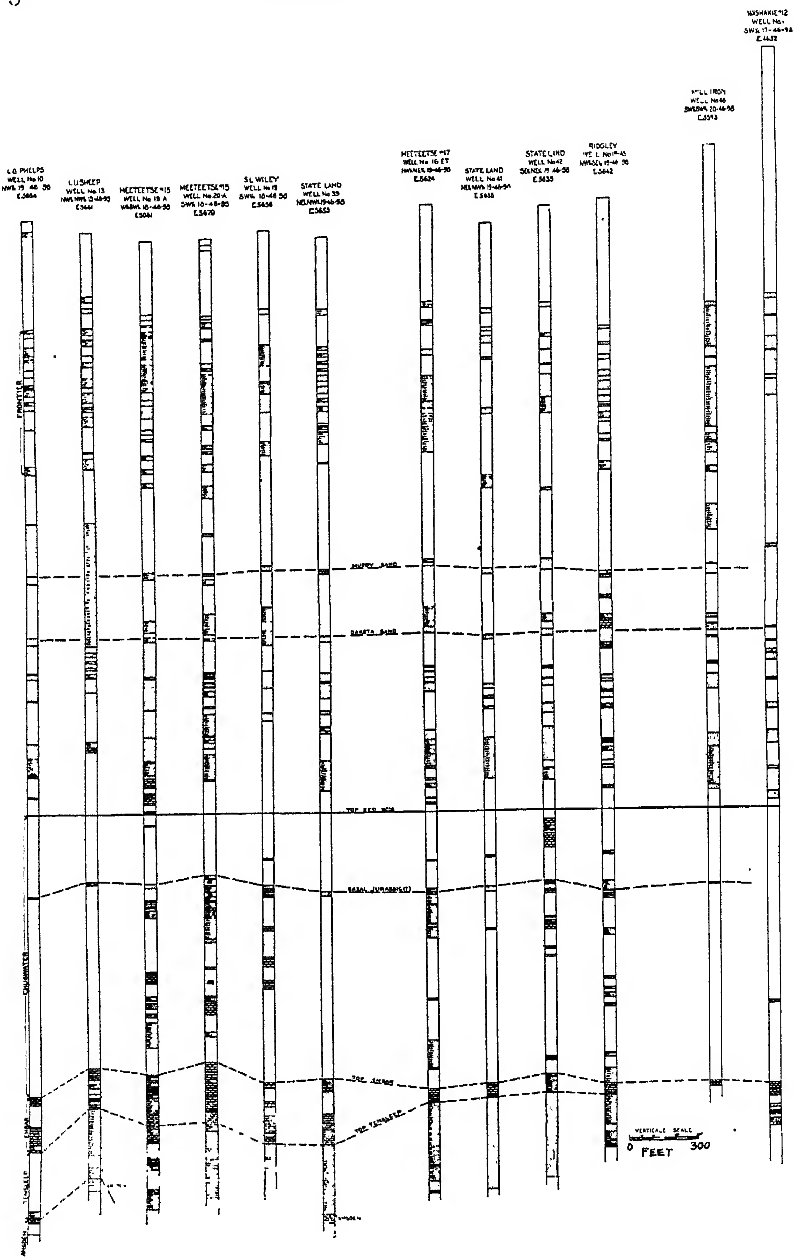

FIG. 2.—Logs of Grass Creek wells that have penetrated Embar-Tensleep horizon.

is persistent. The top of the Tensleep is an erosional surface—an unconformity exists.

Near Douglas, Converse County, Wyoming, on the north flank of the Laramie Mountains, Satanka (otherwise known as "Apache") red shales are overlain by Forelle or Minnekota purple lime (Darton's "crinkly lime"). These two Permian members not recognized at Grass Creek rest

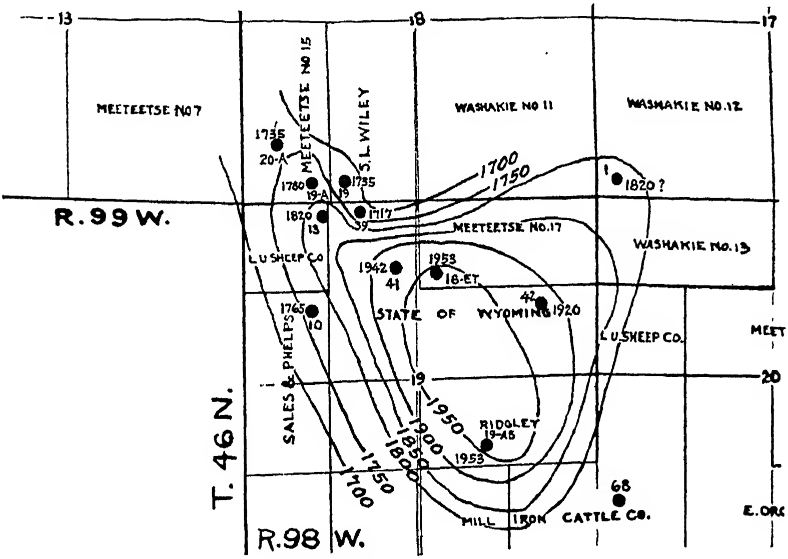

FIG. 3.—Contours on top of Tensleep sand, showing dome at end of Tensleep time. Elevation in feet assumed. Width of area mapped, approximately 2¼ miles.

on the clearly eroded surface of the Tensleep. No Embar is present. Darton also noted the unconformity here and farther west on the Casper Mountains and proposed the name "Casper" for the Carboniferous rocks, "chiefly Pennsylvanian, corresponding to the Tensleep, Amsden, and Madison."[1]

Lee says that a well-marked post-Pennsylvanian erosional unconformity exists both in Colorado and in Wyoming.[2]

[1] N. H. Darton and C. E. Siebenthal, *U. S. Geol. Survey Bull. 364* (1909), p. 13.

[2] Willis T. Lee, "Correlation of Geologic Formations between East-Central Colorado, Central Wyoming, and Southern Montana," *U. S. Geol. Survey Prof. Paper 149* (1927), p. 8.

Embar.—By the end of Red-bed deposition the Embar beds had been warped; the "high" had assumed a new position (Fig. 4). A study of the logs shows that this adjustment occurred in post-Embar time. Notice that a bed approximately 300 feet below the top of the Red-beds has a structure very similar to that at the top of the Embar.

Brainerd and Keyte[1] have during their studies in northeastern Big Horn Basin noted that the Jurassic fauna, contrary to the earlier conception, are found well down in the Red-beds, also that an unconformity marks the beginning of Jurassic deposition.

This Embar "high" more nearly occupies the position and alignment of the present structure, though it had not assumed the abrupt, sharp fold revealed to-day (Fig. 6).

Subsequent folding.—Study of logs suggests that following Red-bed deposition there were no important adjustments during the period represented in the logs. For example, little or no adjustment is evident in either the Dakota or Muddy sand, though it should be borne in mind that neither sand seems to be continuously present in the field. Results of study of the Frontier are not so clear because of the large number and non-uniform character of the sands. Probably some settling (consolidation of sediments) occurred during this post-Red-bed interval.

Hewitt[2] says some of the structural warping in the Big Horn Basin occurred during the early and middle Eocene. Blackwelder[3] states that the most important folding of this period took place between the close of Cretaceous and Lower Eocene. This is commonly known as the "Laramide diastrophism." He says that post-Cretaceous folds were completely truncated during early Eocene; also, that further deformation followed early Oligocene and preceded the Pleistocene.

For comparison with earlier structure, contour maps have been prepared to show present structure of the Tensleep, Embar, and Chugwater (Figs. 5–7), and a structure map of the Frontier by Fred E. Wood and E. L. Estabrook is included by courtesy of the Midwest Refining Company.

[1] A. E. Brainerd and I. A. Keyte, "Some Problems of the Chugwater-Sundance Contact in the Bighorn District of Wyoming," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 7 (July, 1927).

[2] D. F. Hewitt, "Geology and Oil and Coal Resources of the Oregon Basin, Meeteetse, and Grass Creek Basin Quadrangles, Wyoming," *U. S. Geol. Survey Prof. Paper 145* (1926), p. 68.

[3] Eliot Blackwelder, "Post-Cretaceous History of the Mountains of Central-Western Wyoming," *Jour. Geol.*, Vol. 23, No. 2 (1915), p. 97.

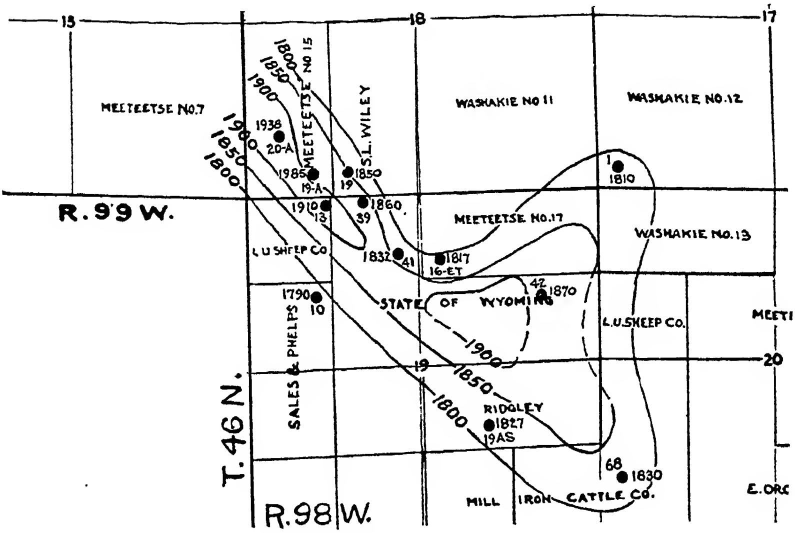

FIG. 4.—Contours on top of Embar (Phosphora) lime member, showing structure before end of Chugwater time, possibly at beginning of Jurassic. Elevation assumed.

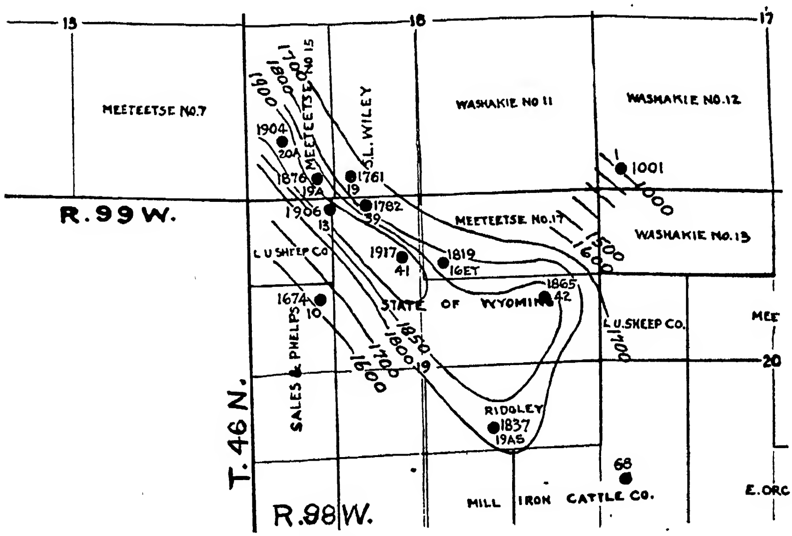

FIG. 5.—Contours on top of Tensleep sand, showing present structure. Sea-level elevations.

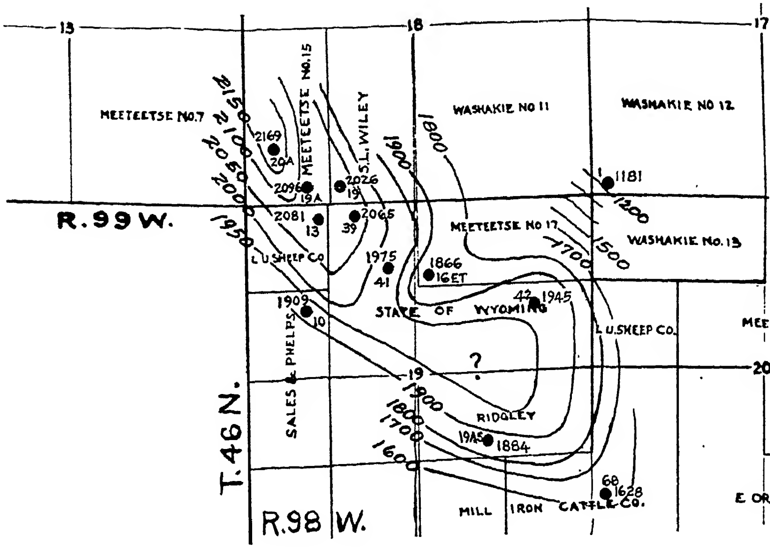

FIG. 6.—Contours on top of Embar, showing present structure. Sea-level elevations.

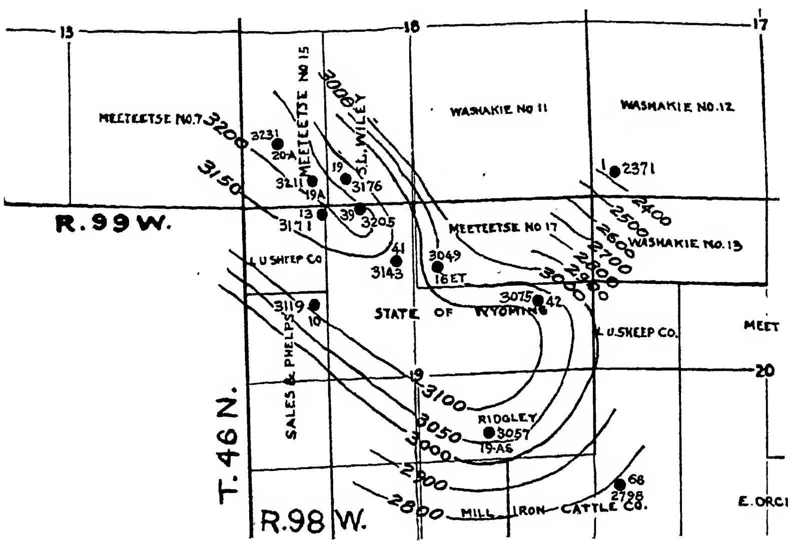

FIG. 7.—Contours on top of Chugwater (Red beds), showing present structure. Sea-level elevations.

CONCLUSION

At Grass Creek a fold existed at least as early as post-Madison time. A "high" or basement fault may have existed in pre-Cambrian time. There were four subsequent movements—post-Tensleep, pre-Jurassic, the Laramide, and post-Oligocene.

The Rocky Mountain system began to be formed near the end of Laramide time, whereas the preceding evidence shows that a fold existed at Grass Creek as early as post-Tensleep, if not earlier.

It is suggested that many of the domal structures in the Big Horn Basin and elsewhere have a similar early origin.

OIL AND GAS FIELDS OF LOST SOLDIER DISTRICT, WYOMING[1]

J. S. IRWIN[2]
Denver, Colorado

ABSTRACT

The commercial oil and gas pools are on crests of closed anticlines and domes except in the General Petroleum field, where oil is found in variable shaly sandstone beds on a pitching anticline without structural closure. The oil sand of the G. P. field (G. P. sand) is not productive elsewhere even on closed structures.

Commercial oil is found in the Mowry shale on the crests of the three sharpest folds—Little Lost Soldier, Wertz, and Ferris. It is not found in the Mowry shale on the gentler folds or elsewhere. Seemingly the maximum fracturing and other mechanical effects peculiar to the crests of sharp flexures are necessary to the formation of the shale oil pools or pockets.

The productivity of the structures, other factors being equal, is in close relation to the extent to which they are fractured and faulted. Burial of the productive sand beneath a great thickness of shale is equivalent to diminution in faulting, since the faults may be sealed or may not persist to great depths. The more numerous and open the faults, the greater the tendency toward an oil pool or to barrenness through more or less complete leakage. The fewer and tighter the faults, the greater the tendency toward a gas pool or to barrenness through lack of migration and accumulation.

With the Lost Soldier and many other oil and gas fields of the Rocky Mountain region as confirmatory evidence, it may be said that, in the post-Paleozoic strata of the region (1) water in an upper sand is not indicative of what is to be expected in lower sands, whether oil, water, or gas; (2) gas, as the predominant product in an upper sand, means that lower sands may be expected to be primarily gas sands; and (3) oil, as the predominant product in an upper sand, indicates that lower sands are likely to be primarily oil sands.[3]

INTRODUCTION

Previous reports on the oil and gas fields of the Lost Soldier district, Wyoming, are by Fath and Moulton[4] and by E. W. Krampert.[5]

The report of Fath and Moulton gives details of structure as inter-

[1] Read before the Association at the Tulsa meeting, March 24, 1927. Manuscript received by the editor, December 14, 1927. Published by permission of Frank E. Kistler and Company and of the Producers and Refiners Corporation.

[2] 935 St. Paul St.

[3] J. S. Irwin, "Faulting in the Rocky Mountain Region," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 127–28.

[4] A. E. Fath and G. F. Moulton, "Oil and Gas Fields of the Lost Soldier–Ferris District, Wyoming," *U. S. Geol. Survey Bull. 756* (1924).

[5] E. W. Krampert, "The Oil Fields of the Rawlins–Lost Soldier District, Wyoming," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), pp. 131–46.

preted from the meager exposures and from the development as of the year 1920. Much of their work was a valuable contribution, but parts had become obsolete by the time of publication in 1924.

Krampert's report, published in 1923, gave a satisfactory account of the history and stratigraphy of the district in general and of the structure and development of the Little Lost Soldier field in particular.

The structure of the entire Lost Soldier district as known at present, and the relation of oil and gas accumulation to the structure, is the subject of this paper.

GENERAL GEOLOGY

The Lost Soldier district, situated in south-central Wyoming, includes the Little Lost Soldier, Wertz, Mahoney, Ferris, Sherard, and Bunker Hill domes; the O'Brien Springs anticline, and the Bell Springs, Buck Springs, and General Petroleum (or "G. P.") structures.

The area is a highly folded element, relatively depressed with respect to the Sweetwater-Ferris Mountain uplift on the north and the Rawlins Hills uplift on the south, and it is relatively uplifted between the Great Divide or Red Desert Basin on the west and the Hanna Basin on the east. Strata of Tertiary age fill the Red Desert and Hanna basins. Paleozoic strata and Archean granite are exposed in the Sweetwater and Rawlins uplifts. Cretaceous rocks occupy the district with which we are concerned, but are largely covered by alluvium, lake deposits, and wind-blown sand.

The Bell Springs and Sherard folds are in alignment with, and form the northern terminus of, the Miller Hill–Lake Valley–Rawlins Hills major fold, which extends almost due north from the Sierra Madre Mountains (Continental Divide) almost to the Ferris Mountains. The Wertz-Mahoney-Ferris anticline and the O'Brien Springs anticline have northwest-southeast to east-west axes, parallel with the Sweetwater-Ferris Mountain uplift, of which they are evidently subsidiary folds. The axis of the Little Lost Soldier dome is transitional in direction between the north-south and east-west folds.

The existence of folds transitional in direction between the north-south and the northwest-southeast trends of the major uplifts, and the fact that the east-west O'Brien Springs axis can be traced practically continuously into the north-south Sherard axis, strongly suggest to the writer that all the folds of the district are of the same generation.

This view has already been expressed by Hintze[1] in a review of Fath

[1] F. F. Hintze, "Review of *U. S. Geol. Survey Bull. 756*," *ibid.*, Vol. 9 (1925), pp. 363–64.

and Moulton's report, wherein he seems to prove untenable the Fath and Moulton theory of separate periods of folding for the east-west and for the north-south folds; and this corresponds with Ball's[1] general conclusion that "all the minor folds of Wyoming were formed during the period of formation of the major uplifts."

STRATIGRAPHY

Those formations which are actual or prospective producers of oil and gas, together with those formations which are involved in surface and subsurface structural studies, will be discussed briefly. The Dakota sandstone and the strata immediately below it but above the Morrison formation are considered in some detail in an attempt to clear up the confusion that exists in certain published reports, but which has long since been harmonized by those in close touch with the district (Fig. 1).

A tabulation of all the sedimentary rocks is presented as a brief summary of the stratigraphy (Table I).

CARBONIFEROUS

The oldest and deepest formations which may be expected to yield oil in the Lost Soldier district are the Madison limestone (Mississippian) and the Amsden and Tensleep formations (Pennsylvanian). Of these formations the Tensleep, a porous to quartzitic sandstone approximately 200 feet thick, is the most promising reservoir rock.

Oil rather than gas is to be expected in these Carboniferous formations; and the oil, if found, is almost certain to be black and of low gravity, in conformity with all oil occurrences known to date in the Carboniferous of the northern Rocky Mountain region.

The Amsden and Madison formations have not yet been reached by drilling; and only one well, located in a structural saddle, has reached the Tensleep sand. A deep test on Ferris dome is now being drilled for the Tensleep. Structurally, and in the matter of depth, the Little Lost Soldier dome is the most favorable place to test the Carboniferous strata.

PERMIAN AND TRIASSIC

The alternating gray limestones and red and gray shales comprising the 200-foot interval between the Red-beds proper (Chugwater) and the Tensleep sandstone, correspond in position and somewhat in lithology with the Embar formation of Permian age, which yields black oil in the Big Horn Basin and along the Wind River Mountain front. This series

[1] Max W. Ball, "Relative Ages of Major and Minor Folding and Oil Accumulation in Wyoming," *ibid.*, Vol. 5 (1921), p. 49.

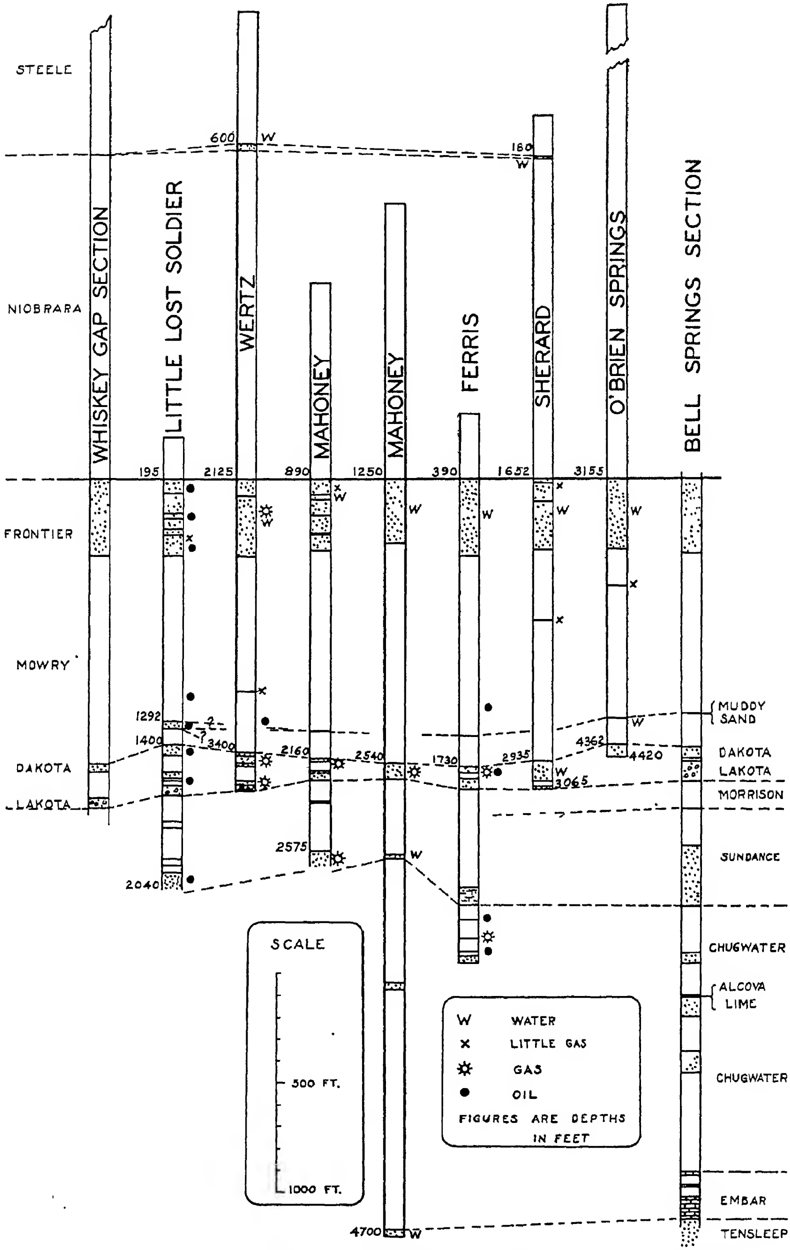

FIG. 1.—Correlation of well logs and measured sections, Lost Soldier district.

TABLE I

GENERALIZED STRATIGRAPHIC SECTION, LOST SOLDIER DISTRICT

Age	Group	Formation	Approximate Thickness (Feet)	General Character
Quaternary		Alluvium and wind-blown sand		Soil, lake deposits, and active sand dunes
Upper Cretaceous	Montana	Mesaverde	2,000–3,000	Alternating thick sandstones, subordinate shales, and some coal. Resistant to erosion and forms hogback ridges which partly encircle the uplift. Full thickness ordinarily not present
		Steele shale	4,125	Dark gray shale with sandy beds prominent at top and bottom and one especially prominent sandstone member 800 feet below top
	Colorado	Niobrara shale	1,450–85	Top, marked by thin yellow argillaceous limestone beds, or by variable G. P. sand, or by both. Chalky shale phase occurs 300 feet above Frontier
		Carlile shale		Not differentiated. Included in Niobrara
		Frontier	900±	Top 350 feet, composed of three to five sandstone beds separated by thin shale or sandy shale. Lower part composed of soft gray shale and sandy shale containing a few thin, lenticular sandstones
		Mowry shale	350±	Hard, brittle, siliceous, organic shale. Black, but weathers silver-gray. Fish scales in practically every hand specimen
		Thermopolis shale	50	Here restricted to those soft, black shales between Muddy sand and Mowry shale
Upper Cretaceous (Lower part possibly Lower Cretaceous)	Dakota	Dakota	100–300	Muddy sand at top is thin, soft, shaly, and not everywhere present. Dark shales and sandy shale, 120–50 feet thick, separate Muddy sand from underlying Dakota sand, which is hard, light-colored, quartzitic, and 25–35 feet thick. Variegated shales (15± feet), ordinary light-colored and sticky between Dakota and Lakota sands. Lakota sand, 50+ feet thick, ordinarily conglomeratic
Lower Cretaceous?		Morrison	175	Variegated shale and variable sandstone

TABLE I—*Continued*

Age	Group	Formation	Approximate Thickness (Feet)	General Character
Jurassic		Sundance	400	Fossiliferous gray and green shale and subordinate limestone comprise upper 115 feet. Lower part is sandstone 270± feet thick, non-red at top and red at bottom
Triassic		Chugwater ("Red-beds")	1,200	Red shale, sandy shale, and sandstone, with Alcova limestone member 12 feet thick, 400 feet below top of formation
Permian		Embar	215	Light purple to light gray sandy and cherty limestone. Members separated by red shale near top and by thin gray shale in lower part
Pennsylvanian		Tensleep sandstone	200	White quartz sandstone
		Amsden	200	Gray cherty limestone and shale, and red sandstone and shale
Mississippian		Madison limestone		Light gray resistant limestone
Cambrian		Deadwood?		Quartzitic sandstone and quartzite
Pre-Cambrian				Crystalline rocks

does not seem particularly promising as a reservoir rock but will be incidentally tested in process of drilling to the more promising Tensleep and other Carboniferous horizons.

Chugwater formation.—The Chugwater formation of Triassic age comprises a series of sandstone, sandy shale, and shale, predominantly brick-red in color, lying above the Embar equivalent and below the Jurassic beds. The name "Red-beds," intended to be synonymous with "Chugwater," is misleading, since it implies the inclusion of all red-colored beds, whereas parts of the Embar equivalent and some of the Lower Jurassic beds are red. The Chugwater, as restricted, according to a section measured at Bell Springs, includes 1,200 feet of beds between the uppermost limestone of the Embar equivalent and the base of the thick sandstone series of the Lower Jurassic known in the field as the "Sundance sand."

The Chugwater formation has been completely penetrated by but

one well in the district, that of the Ohio Oil Company, located in the structural saddle between Mahoney and West Ferris domes. The formation, composed as it is of red sandstone and shale practically devoid of organic matter, is not promising as a source of oil; but where faulting and fracturing occur to a considerable extent, it may be petroliferous through migration from extraneous sources. It will be tested in due time by wells headed for the underlying Carboniferous strata.

Three wells at Ferris, with a daily capacity of a few barrels, produce black oil from pink and red sandy beds below the main body of the Sundance sand. These beds are in a somewhat debatable zone but are here considered to be in the upper Chugwater. This is stratigraphically the lowest commercial production in the district.

JURASSIC

The Sundance formation of Jurassic age is of major importance in the Lost Soldier district as a prolific source of oil and gas. At the Bell Springs outcrop the formation is 400 feet thick, of which thickness the upper half is white, green, and gray in color and the lower half is more or less red. A zone of sandstone approximately 300 feet thick, with its upper surface 100 feet below the top of the formation, is white or light gray in the upper 100 feet, and in part red throughout the lower 200 feet. This zone is the highly productive gas and oil sand known as the "Sundance sand." As found in the wells, the proportion of white to red differs greatly, some of the wells having reported practically all red sand and shale.

The Sundance sand yields large quantities of gas at West Ferris and Mahoney domes, and oil of intermediate grade has recently been discovered in it on Little Lost Soldier dome.

The interval from the top of the Dakota sand to the top of the Sundance sand is 450 feet at Mahoney dome, 350–550 feet at Ferris and West Ferris, and 580 feet in Prairie Oil and Gas Company's Well No. 49-A at Little Lost Soldier. The minimum interval in the Mahoney-Ferris district is probably due to the absence of a part of the Lower Cretaceous beds at the unconformities, and the larger interval of beds at Ferris can be explained by inclination of beds on the flanks of the sharp fold. The maximum interval at Little Lost Soldier is probably the approximate normal.

LOWER CRETACEOUS(?)

Morrison formation.—The Morrison beds, composed of pink, red, and gray shale and possibly some sandstone, are not productive of oil

and gas in the Lost Soldier district. At the Bell Springs outcrop the thickness of the Morrison is 175 feet or slightly less.

No satisfactory horizon-marker exists, either in the outcrops or in well records, whereby the Morrison can be separated from the Sundance; and their exact differentiation, being of no practical value, is ordinarily not attempted.

CRETACEOUS

Dakota group.—The Morrison formation is succeeded unconformably by a conglomerate and sandstone member 40–60 feet thick. This is the "Lower sandstone" of Lee's[1] "Dakota group," the Lower Cretaceous conglomerate of Hares,[2] the basal member of the Cloverly formation of the Big Horn Basin (Lee) and of the Hanna Basin (Bowen), and, according to Lee, corresponds with some parts of the Lakota sandstone of the Black Hills. The name "Cloverly" is now little used in the region, and "Lakota" is the term commonly applied to the basal conglomerate if it is mentioned separately.

Above the basal conglomerate member and separated from it by variegated shales, generally light in color, and ranging in thickness from a very few feet to 50 feet, is a hard, white, fine-grained sandstone, in many places iron-stained and quartzitic in its weathered aspect. This is the "Middle sandstone" of Lee's "Dakota group," and it is recognized as the "Dakota sand" by all those familiar with the northern Rocky Mountain region. The thickness is not uniform but is ordinarily between 20 and 50 feet.

Above the "Dakota sand" and below the unique and unmistakable Mowry shale are black- to rust-colored shale, sandy shale, and shaly sandstone, altogether approximately 200 feet in thickness. This interval has long been known as the Thermopolis shale; and the included sandy beds, where sufficiently distinct to be regarded as a member, have been called the "Muddy sand."

Lee correlates the Muddy sand with the Upper sandstone of his "Dakota group" (Bellevue, Colorado, section), which procedure, if accepted, confines the Thermopolis shale to that interval between the Muddy sand and the Mowry shale.

According to the age classification of the U. S. Geological Survey,

[1] W. T. Lee, "Correlation of Geologic Formations between East-Central Colorado, Central Wyoming, and Southern Montana," *U. S. Geol. Survey Prof. Paper 149* (1927), p. 18, and Plate 1.

[2] C. J. Hares, "Anticlines in Central Wyoming," *U. S. Geol. Survey Bull. 641* (1917), p. 244.

Lee's[1] Lower and Middle sandstone members of the Dakota group are of Lower Cretaceous age, and the Upper sandstone is the only representative of the Upper Cretaceous in the group; consequently it is the only member which can be given the name "Dakota sandstone." But, granting that Lee's regional correlations, as published by the U. S. Geological Survey, are correct, he is forced to the absurdity of calling the Muddy sand the Dakota sand, a procedure with which no one familiar with the origin and usage of the name "Muddy" will agree.

To the writer, the suggestion of Lee is the most reasonable way out of the difficulty. In Lee's opinion, since the few fossils found in them do not establish the geologic age of the rocks beyond question, it is better to base the division on structural relations, and he accordingly takes the widespread basal conglomerate at the great unconformity above the Morrison as the marker of the general advance of the Cretaceous (Upper Cretaceous) sea. Thus would Lee assign the entire Dakota group to the Cretaceous (Upper Cretaceous), but this interpretation, although published by the U. S. Geological Survey, has not been formally approved by that body.

The Lakota conglomerate ("Lower sandstone") and Dakota sand ("Middle sandstone") have yielded the greater part of the oil and gas of the Lost Soldier district. The Muddy sand ("Upper sandstone") is not recognized at Little Lost Soldier, Wertz, and Mahoney domes, but is reported as sandy shale or sandstone 5 feet or less thick at Ferris, where it lies 140 feet above the Dakota sand and yields a small amount of oil.

The erroneous statement made by Fath and Moulton,[2] to the effect that the "Muddy sand is the reservoir rock in the Lost Soldier (Little Lost Soldier) dome at a depth of 1,375 feet," has not been corrected in publications, to the writer's knowledge, and such correction is here made.

It is a fact accepted by all who have kept in touch with development in the Lost Soldier district that the reservoir rock, 1,375 feet deep at Little Lost Soldier, 3,400 feet deep at Wertz, 2,160 feet deep at Mahoney, and 1,750 feet deep at Ferris, is the Dakota-Lakota series. Further, it is agreed[3] that the Muddy sand (Upper sand of the Dakota group of Lee and, in the Big Horn Basin, Wyoming, a sandstone member of the Thermopolis shale) is not recognized except as a very thin sandy shale or sandstone zone at Ferris and as a soft shaly sandstone or sandy shale in the Bell Springs outcrop.

[1] W. T. Lee, *op. cit.* [2] A. E. Fath and G. F. Moulton, *op. cit.*

[3] F. F. Hintze, Elfred Beck, E. W. Krampert, the writer, and others, verbal communication.

Fath and Moulton recognized the Muddy sand at Bell Springs and write correctly, as follows:

The upper sandstone (Muddy sand) of the Cloverly is present in the Bell Springs area only as a shaly sandstone and measures 20 to 25 feet in thickness. In some places it may be represented only by a sandy zone in the shale, and in such places the top of the Cloverly might be difficult to discern.

It is just this tendency to disappear which caused the error in the Whiskey Gap section of Fath and Moulton published by Lee. Lee, commenting on Fath's Whiskey Gap section, states that

. . . . he failed to find the upper sandstone of the Bellevue section (Muddy sand) where he examined these rocks. Probably in this as in other places the upper sandstone is variable and locally absent. Fath, who examined the Lost Soldier and Ferris oil fields, found the upper sandstone 30 feet thick, but makes no mention of the middle sandstone, probably because at the time of his examination little attention was given to the lower beds.

Fath's error is obvious to one familiar with the Whiskey Gap outcrop. The Upper sandstone of Fath's section is actually the "Middle" or true Dakota sandstone, and Lee is right in stating that the Upper sandstone (Muddy sand) is absent. Finding but two sandstones present, Fath, evidently unfamiliar with the usage of the term, called the highest sandstone he found the "Muddy sand."

The highest sandstone in the Whiskey Gap section is the typical hard, white to iron-stained, resistant Dakota sandstone—its top 150 feet above the top of the lower conglomeratic member, with a shale interval occupying the soil-covered area between the two hogbacks.

Above the Dakota member at Whiskey Gap the typical black shales occur, just as they do at Bell Springs, but here all that remains of the Muddy sand are a few sandy slabs a fraction of an inch in thickness. The cone-in-cone limestone which occurs at the base of the Muddy sand at Bell Springs can be observed in the section 1 mile southeast of Whiskey Gap, but shale only occurs above it.

A correlation of the Dakota group sections of Lee, Fath, and the writer, with typical well records of the same horizons in the several fields of the district is given in Figure 7.

Mowry shale.—The Mowry shale, typically developed, occupies the interval between the Dakota-Thermopolis sand-shale series below and the Frontier formation above. It is hard, brittle, thinly laminated, and highly organic, and has been accepted generally as the source of at least a part of the oil in stratigraphically adjacent sandstones.

The Mowry shale is itself productive of oil at Little Lost Soldier,

Wertz, and Ferris. No sand members are known to occur in it here, so that it would seem that the oil accumulation is made possible by fissures, faults, and pockets induced by the intense deformation along the axes of the sharper folds. Under such conditions occurrence of oil in the Mowry is not proof that its source is in that formation. The facts that the Mowry is obviously organic and that oil can be distilled from it are the reasons for regarding it as a source of oil.

Frontier formation.—The upper 350 feet of the Frontier formation is composed largely of five thick gray sandstone members, separated by subordinate shale breaks. The lower part is composed of soft gray shale, containing a few thin and probably lenticular sandstone beds.

The Frontier sandstones yield commercial oil at Little Lost Soldier, and a very small but profitable gas pool at Wertz. At Mahoney dome only a showing of gas occurred in the upper sandstones, and at O'Brien Springs and Sherard dome one of the lower thin sandstone members yielded showings of gas. At Ferris the upper sandstones are water-bearing, and such oil as occurs in the lower, thin sandstone members amounts to little more than a showing. Thus it appears that in the district as a whole the Frontier (Wall Creek) sands are of small importance.

The approximate minimum interval from the top of the Frontier sand to the top of the Dakota sand, the contoured horizon on the maps, is 1,200 feet at Little Lost Soldier, 1,255 feet at Wertz, 1,300 feet at Mahoney, 1,350 feet at Ferris, 1,282 at Sherard, 1,207 at O'Brien Springs, and 1,200 at Bell Springs.

Niobrara formation.—The Niobrara formation, composed of shale with a non-uniform sandy zone at the top, comprises the interval between the Frontier and the Steele formations. The lower part of this interval corresponds in position with the Carlile shale, but the differentiation has not been attempted and would seem to serve no useful purpose if accomplished. The sandy zone at the top ranges through hard sandstone to sandy shale, to seemingly complete absence of sand, as evidenced by the resistant sandstone rim rock formed by it at Little Lost Soldier, the low, rounded, half rim on the south side of Mahoney dome composed of this horizon in its sandy shale phase, and the absence of any noticeable sandy beds at this horizon in the outcrops on the Ferris Mountain front.

This sandy zone has yielded commercial oil at but one locality in the district, namely, the General Petroleum (or "G. P.") field southeast of Ferris. The structure in that field is interpreted from rather inadequate data as being a plunging anticline, without structural closure. Elsewhere, where the sandy zone is under cover on closed structures, as at Wertz and Sherard, it is a water sand.

The sandy zone is variously referred to as the "G. P. sand," the "G. P. stray," and the "Niobrara sand." Some workers in the district regard it as the top of the Niobrara formations; other consider it the basal member of the Steele shale. The interval from the top of the G. P. sand to the top of the First Frontier sand is 1,515 feet at Wertz and 1,530 feet on Sherard dome.

Steele shale.—The Steele shale is only of technical interest, as it is not productive of oil or gas. The formation is 4,125 feet thick near Whiskey Gap, if all the prominent sandstone beds except the lowest in the debatable zone between the Steele and the Mesaverde formations be assigned to the latter. The expected sandstone bed, the top of which is 850 feet below the base of the Mesaverde formation in the Whiskey Gap exposure, is 100 or more feet thick. It possesses sufficient resistance here and there to form hogbacks and is similar in position and, superficially at least, in appearance to the Morapos sandstone of northwestern Colorado.

Mesaverde formation.—The Mesaverde formation is of interest only because of its resistant sandstone members which form rim rocks around a part of the district. These rim rocks afford the principal basis for the determination of the geologic structure. The grayish-white to white massive sandstone, its top 465 feet above the top of the Steele shale and 1,260–1,315 feet above the top of the upper Steele sandstone member referred to in the preceding paragraph, serves as the most satisfactory horizon marker in the district. It is further identified by a brown, ferruginous sandstone approximately 1 foot thick and 4–6 feet above it, in which a large *Ostrea* is plentiful.

STRUCTURE

The structural configuration of the Lost Soldier district is represented on the accompanying maps (Figs. 2, 4, 6, 9, and 10) by contours which show the elevation of the top of the Dakota sandstone ("Middle sandstone" of Lee's "Dakota group") above sea-level. All available surface structural control has been graphically projected downward to the top of the Dakota sand by means of numerous vertical sections, and the resulting structural contours have been corrected in accordance with subsurface data obtained in process of development.

LITTLE LOST SOLDIER DOME

Structure.—The structure is an elliptical dome possessing 3,500 feet of independent closure. The southwest or basinward flank reaches a maximum inclination of 45°, and the northeast or mountainward flank, contiguous to the Wertz dome, dips approximately 35° where most highly

inclined. The axis of the fold pitches approximately 25° northwest and southeast from the crest.

The large number of normal dip faults of the epi-anticlinal type on the northeast flank of the dome is a most remarkable feature. Observation and mapping of these faults in unusual detail is made possible by the exposure of the G. P. sand in its more resistant phase at just the right locality to delineate the deformation.

The faults[1] exert a profound effect on oil accumulation in the structure, as is attested by the following facts.

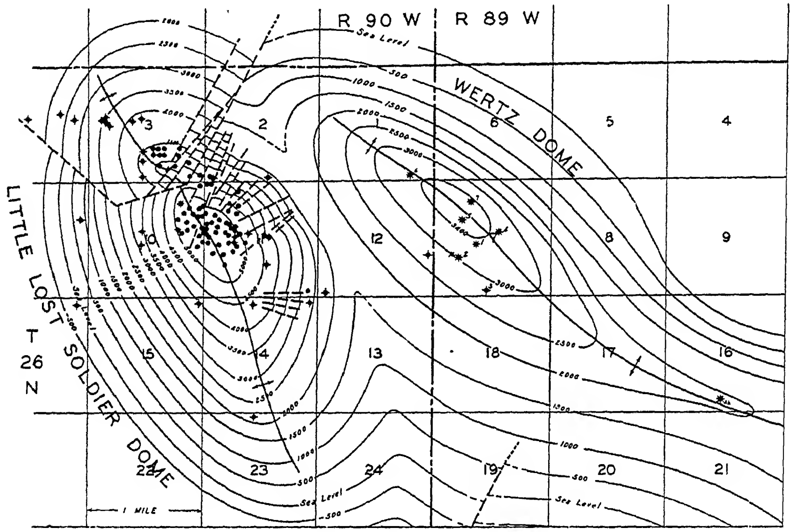

FIG. 2.—Structure contours on top of Dakota sand, Little Lost Soldier and Wertz domes, Wyoming. Datum, sea-level. Contour interval, 500 feet.

1. Intercommunication between the Dakota and Frontier sands along fault planes has been proved by the behavior of certain wells.

2. Abnormally high temperatures were recorded at the time a certain well was known to be drilling through a fault. This increase in temperature the writer believes to be due to the transmission of deeper-seated temperatures by fluids along the fault plane.

Certain exceptionally large wells believed to derive their oil from fault fissures above the sand yielded oil with a temperature of 120°, which is 50° above normal.

[1] J. S. Irwin, "Faulting in the Rocky Mountain Region," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 117–29.

3. Commercial oil production extends 600 feet lower on the northeast flank in some of the relatively elevated fault blocks than it does on the southwest flank, where there is little, if any, faulting. Six hundred feet is the approximate amount of the throw of some of the larger faults. The effect is an oil pool perched off-center with respect to the apex of the dome and favoring the flank highly dissected by faults.

4. It has been possible to measure the throw of many of the faults at the surface and to recognize from subsurface data approximately the same throw in the Dakota sand. Wells which pass through the fault planes find the section shortened not only by the amount of the stratigraphic throw (500 feet maximum) but by an additional amount (500 feet maximum), which seems best explained by thinning under flowage. Moreover, the downthrown blocks, which could possess no lessening of interval due to fault throw, exhibit 500 feet (maximum) thinning. It is therefore concluded that a general stratigraphic thinning, resulting from deformation, exists on the northeast flank.

The composite cross section (Fig. 3) shows the position of the Dakota-Lakota sands on both an upthrown and a downthrown block. The position of the Sundance sand as it would occur if neither faulting nor thinning existed is shown by the dashed lines.

It seems reasonable to conclude that the openness of the fault planes at Little Lost Soldier permitted the free migration of oil and gas from a lower source to the Frontier sands, since these sands are either water-bearing or contain minor quantities of gas in all the other closed structures of the district. Selective leakage of gas from the intercommunicating sands to the surface at Little Lost Soldier, where the faulting is excessive and the depth of burial slight (200 feet), is the best explanation that can be offered for the fact that oil only occurs here in sands (Sundance to Frontier, inclusive) which yield gas and water in the other closed structures of the district.

Production.—The commercial production of Little Lost Soldier dome is entirely oil. The First Frontier (First Wall Creek) sand at a depth of 200 feet on the crest is the shallowest producer in an area of 160 acres, and five or more lower Frontier sand members yield some oil near the crest. The Mowry shale at a depth of approximately 1,100 feet yields a few wells of 200 to 700 barrels capacity.

The most important oil production to date has come from the Dakota and Lakota sands, minimum depth 1,375 feet. The dark-colored, shaly sand member just above the Dakota, known as the Muddy sand, yields a small amount of oil of little or no importance. The Dakota-Lakota

wells vary from 300 to 4,000 barrels per day, with 1,500-barrel wells considered an average. The Dakota-Lakota productive area is approximately 350 acres. Recently several good wells have been completed in the Sundance sand at a depth of 2,050 feet. The boundary of oil production in the Sundance, where determined, is nearly the same as in the Dakota-Lakota.

The normal daily production of the field from 1924 to 1927 was approximately 5,000 barrels per day. The total production of oil to April 30, 1927, was 9,339,156 barrels. The American Petroleum Institute estimate of future production, as of January 1, 1926, was 10,000,000 barrels,

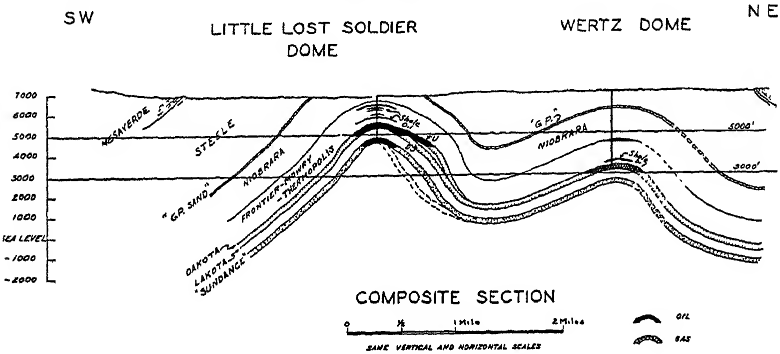

FIG. 3.—Composite section through Little Lost Soldier and Wertz domes. Depths in feet.

at which time 6,889,145 barrels had been produced and the oil in the Sundance sand had not been discovered.

The oil from the Dakota sand has a gravity of 32°–33°. It is exceptionally high in paraffin, so much so that it acquires the consistency of vaseline at ordinary autumn temperature. The gasoline yield by distillation is 12–15 per cent.

The Sundance oil has a gravity of 30° and a gasoline yield of 12.6 per cent by distillation.

The Frontier sand oil has an average gravity of 31° and contains a little less paraffin than the Dakota oil.

The composite gasoline yield of the mixed oils at the refinery by both distillation and cracking is 50 per cent.

The Embar, Tensleep, Amsden, and Madison formations of Carboniferous age have not yet been tested but may be regarded as possible sources of black oil. The Tensleep sand is the most promising of these horizons and will be reached at a depth of approximately 3,500 feet on the crest.

The combination of favorable structure with the least depth obtainable in the district makes Little Lost Soldier dome first choice as a place to test the deeper black-oil horizons.

WERTZ DOME

Structure.—Wertz dome is contiguous to Little Lost Soldier dome and lies within the same partly encircling Mesaverde rim rock. Although their crests are but $2\frac{1}{2}$ miles apart and the surface has approximately the same elevation on both structures, the crest of Wertz dome is 2,000 feet lower structurally than that of Little Lost Soldier dome. In other words, depths to corresponding horizons are 2,000 feet greater on Wertz dome.

The structure is an elliptical dome, slightly smaller and slightly more elongate than Little Lost Soldier, with an independent closure of 1,400 feet above the syncline which separates it from the latter structure. The northeast or mountainward flank dips 50° at the steepest points, and the southwest flank dips 23°, where most highly inclined. The maximum northwest axial pitch observed is 13°. The southeast axial pitch has not been determined with precision, but its average is less than the northwest pitch.

There is already proof of some deformational stratigraphic thinning on the northeast flank of Wertz dome, but development has not proceeded far enough to reveal completely the curve on the Dakota sand. Extreme scarcity of exposures makes the status of faulting indeterminate, although calcite fissure filling and abrupt color changes in isolated shale exposures suggest some faulting. The subsurface data, admittedly inadequate, indicate no faulting of any considerable magnitude. Faults do not seem to be important features on Wertz dome, as they are on Little Lost Soldier dome.

Even if faults of considerable magnitude exist on Wertz dome, the 2,100 feet of comparatively incompetent shale above the Frontier sands and the 3,400 feet of section, largely shale, above the Dakota sand would probably preclude the existence of avenues of migration and escape to the surface. Absence of faults, or their tightness if present, seems best to account for the occurrence of gas to the exclusion of oil on Wertz dome, whereas oil to the exclusion of gas occurs on the immediately adjacent and structurally higher and profoundly faulted Little Lost Soldier dome. In accordance with this view, the writer has long felt that the sands below the Dakota would be oil sands at Little Lost Soldier and gas sands at Wertz. Recently the Sundance sand was found oil-bearing at Little Lost Soldier, and the Lakota sand gas-bearing

at Wertz. Attempts are now being made at Wertz to drill through the high-pressure gas in the Dakota and Lakota sands in order to test the Sundance sand. The Sundance may be expected to be primarily a gas sand.[1]

Production.—The shallowest sandstone member encountered in drilling is the G. P. sand at approximately 600 feet in depth. It carries a small amount of water but no oil or gas.

The Frontier sands at a depth of 2,125 feet on the crest of the structure are water-bearing, with the exception of a small gas pool of approximately 40 acres on the exact apex of the dome. The Frontier gas had an initial pressure of 850 pounds per square inch. Proximity of water wells to gas wells in this sand indicates that no ring of oil exists outside of and under the gas.

The Mowry shale yielded 50 barrels of oil per day for several months in the discovery well but was not productive in the other six wells. Productivity of the Mowry would occur only in open fissures and pockets, and would be expected to be erratic, as it is.

The Muddy sand is not recognized in drilling.

The Dakota sand at a depth of 2,400 feet is the most important productive horizon. The gas pool in this sand on July 1, 1926, was approximately bounded by the 3,100-foot contour and had an area of 410 acres. The original productive area was somewhat larger, possibly 500 acres. The original pressure was 1,840 pounds per square inch, or 367 pounds greater than the accepted normal for the depth.

No ring of oil of any importance exists outside of and under the gas in the Dakota sand, since Well No. 2, Section 7, an edge gas well, 440 feet vertically below the crest, went to water rather than oil. Well No. 3, Section 7, located 660 feet vertically down structure, encountered water, with only a showing of oil.

The only well yet drilled below the Dakota sand reached the second sand, presumably the Lakota, at a depth of 3,547 feet, an interval of 147 feet below the Dakota, and found gas under 1,350 pounds pressure, or 185 pounds less than the normal for the depth.

The occurrence of supernormal pressure in an upper sand and subnormal pressure in a lower sand is anomalous and deserves discussion. There is every reason to believe that the hydrostatic head in the two sands is the same, since their outcrops are within 200 feet of one another and at approximately the same elevation. The explanation for inequality of pressure which seems most satisfactory to the writer is that there is inter-

[1] J. S. Irwin, *op. cit.*, p. 128.

communication between the sands and that during withdrawal of gas from the upper sand the lower sand had been partly depleted before it was penetrated by the drill.

The Sundance sand, not yet explored, should be reached at a depth of approximately 4,000 feet, and may, with considerable confidence, be expected to produce a large amount of gas under very great pressure.

The Carboniferous black-oil horizons are not attractive objectives here on account of depth, 5,700 feet and greater.

The remarkable productivity of the Dakota gas sand on the Wertz dome makes a few production figures seem worthy of a place here.

The discovery well, with initial open flow of 40,000,000 cubic feet, pressure 1,800 pounds, commenced delivering gas to the pipe line on December 31, 1921, and on December 31, 1926, had delivered 21,618,-498,000 cubic feet of gas. Two gas wells completed during 1925 and 1926 contributed an additional 3,682,987,000 cubic feet, making the total metered production from the Dakota sand for the five-year period 25,301,-485,000 cubic feet. Gas unavoidably lost can only be estimated but would probably be almost 2,000,000,000 cubic feet. The average rock pressure in the three Dakota sand wells was 632 pounds on December 31, 1926.

The Dakota gas originally carried 9 pints of gasoline per 1,000 cubic feet and yielded 100–200 barrels of natural gasoline per day at the field drips for two or three years. The natural-gasoline production then gradually declined, in accordance with the decline in volume of gas produced. The remaining gasoline is extracted at an absorption plant. Authentic figures are not presented for the total natural gasoline yield, but an estimate is 250,000 barrels, nearly all of which came from Well No. 1.

BUNKER HILL DOME

Structure.—Bunker Hill dome is a small structure possessing approximately 600 feet of closure squeezed between Wertz dome and the Ferris Mountains. The lower resistant sandstone members of the Mesaverde formation which form the rims of the other folds have not been removed by erosion on Bunker Hill; hence, this dome is the only one in the district which finds topographic expression as an eminence.

Production.—A well drilled near the crest to a depth of 827 feet is the only development recorded. The first 450 or 500 feet of this hole is in Mesaverde, and the remainder in Steele shale. No oil or gas was found. The G. P. sand would be expected at 4,600 feet, the Frontier at 6,050 feet, and the Dakota at 7,300 feet.

On account of excessive depths to prospective sands, the Bunker Hill

dome is not an attractive prospect and could not properly be considered by any but large operators already heavily interested in the vicinity.

MAHONEY DOME

Structure.—Mahoney dome has a broad, fairly flat crest area. Gentle dips of not more than 10° continue outward from the apex toward the west, south, and east. Northward the dip changes gradually from zero at the crest to approximately 10° within a distance of 2,000 feet from the

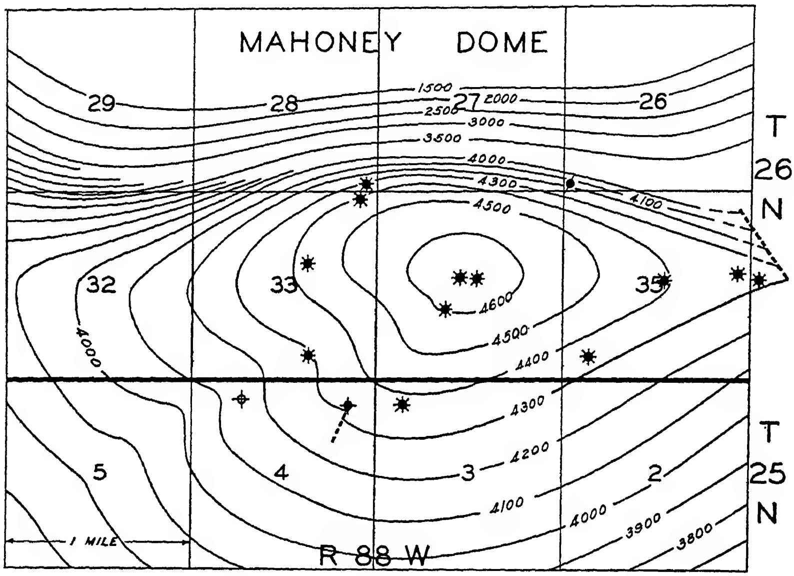

FIG. 4.—Structure contours on top of Dakota sand, Mahoney dome. Datum, sea-level. Contour interval, 100 feet.

crest, where it bends abruptly into 55°. The north-south section across the dome is therefore highly unsymmetrical and is unique in that it possesses two centers of curvature (Fig. 5). The independent closure above the structural saddle between Mahoney and West Ferris domes is only 350 feet, but the effective closure is 2,000 feet or more.

Mahoney dome is evidently not extensively faulted, if at all, near the crest. The entire crest area is under cover of a soil mantle, so that nothing can be observed at the surface. However, the 100-foot contours on the Dakota sand fail to show any faulting. The south rim formed by the outcrop of the G. P. sand (top of the Niobrara) discloses several normal dip faults of very small throw, but it is probable that few, if any,

reach the Dakota sand. Drilling in the vicinity is not sufficient to detect faulting by means of subsurface data. Even if faults exist, they lie largely outside the productive areas of the Dakota and Sundance sands, so that it is assumed that faulting has little or no effect on oil and gas accumulation on Mahoney dome.

Absence of extensive faulting, with consequent lack of avenues of migration and escape, seems to be the best reason why Mahoney dome yields gas to the practical exclusion of oil in the three horizons thus far tested.

Production.—The Frontier sands are water-bearing, with the exception of a small amount of gas encountered by the discovery well on the exact crest. The flow was not of commercial value.

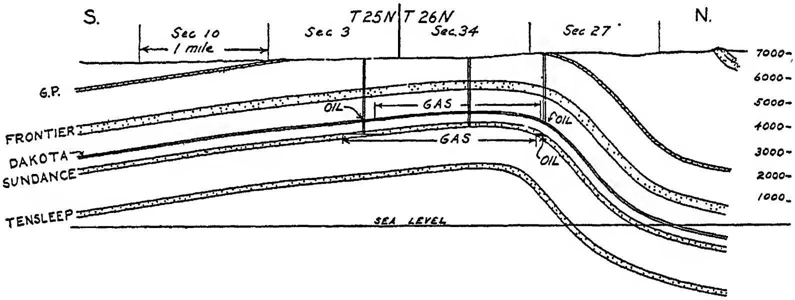

FIG. 5.—Cross section of Mahoney dome. Same vertical and horizontal scales. Depths in feet.

The Dakota sand, reached at 2,160 feet on the crest, has produced large quantities of gas but is now practically exhausted. The initial pressure was 825 pounds per square inch. The Dakota productive area was bounded approximately by the 4,300-foot contour and was approximately 1,600 acres.

Authentic figures for total gas produced from the Dakota sand are not easily available because several companies are involved. Metered production of the largest producing company from inception of production in 1922 to December 31, 1926, was 8,937,718,000 cubic feet. Production of other companies during the period may be assumed as 3,000,000,000; and loss, principally due to fire and to wild flow of the Kasoming discovery well, was probably more than 6,000,000,000 cubic feet. A reasonable figure for the total amount of gas in the Dakota sand is 17,000,000,000 cubic feet.

An insignificant ring of oil surrounding the gas in the Dakota sand is

of technical, but not commercial, interest. Producers and Refiners Well No. 2, Sec. 4, T. 25 N., R. 88 W., on the 4,316-foot contour, found water and a showing of oil and gas. The well might have been commercial had it been possible to complete it. The Midwest Refining Company well in the same section, on the 4,150-foot contour, found water and a showing of oil. Ohio Oil Company Well No. 1, Sec. 36, T. 26 N., R. 88 W., on the 4,342-foot contour, was a commercial gas well. On the north flank Kasoming Well No. 1, Sec. 26, T. 26 N., R. 88 W., on the 4,215-foot contour, was able to produce less than 5 barrels of oil per day for some time, but there was water with the oil. This is 100 feet lower than the gas and oil showing in the edge well on the south flank, but the circumstances do not permit precise statements concerning the difference in elevation between the water levels on the north and on the south flanks. It should be observed that since the sand stratum, 25 feet thick, is inclined 55° on the north flank and only 10° on the south flank, a given amount of oil would have a greater vertical development on the north flank.

The Sundance sand at a minimum depth of 2,575 feet will ultimately be the greatest producer of gas on Mahoney dome. From the inception of production late in 1924 to December 31, 1926, this sand had produced 7,487,524,000 cubic feet of gas. The initial pressure was 1,220 pounds per square inch, and the productive area somewhat greater than 1,600 acres. It is now somewhat less than that.

No horizons below the Sundance sand have been tested on Mahoney dome, although the Tensleep sand was penetrated in the structural saddle between Mahoney and West Ferris and yielded sulphur water. The Tensleep is still a prospective source of black oil higher on the structure.

FERRIS DOME

Structure.—Ferris dome is a sharply folded, elongate dome, having an independent closure of 1,200 feet and a total closure of at least 2,700 feet. The maximum inclination of the northeast flank is 45° and that of the southwest flank is 25°.

Surface evidence of the fold is almost entirely masked by sand dunes; but at a few points where the sand is thin or absent, pits dug in the chalky shale phase of the lower Niobrara reveal the structure in part. At one place the surface axis of the anticline has been located exactly, and, since the axis on the Dakota sand has been determined precisely by subsurface data, the inclination of the axial plane is thus known (Fig. 7). The horizontal offset is 300 feet toward the flank of lesser inclination at a depth of 1,750 feet. This offset is slightly less than the theoretical amount and

indicates that the axial "plane" is not a true plane but is a curved surface, convex toward the gentler-dipping flank.

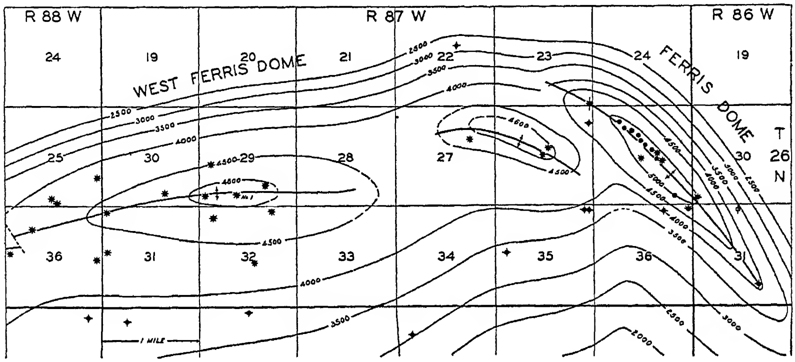

FIG. 6.—Structure contours on top of Dakota sand, West Ferris and Ferris domes. Datum, sea-level. Contour interval, 500 feet.

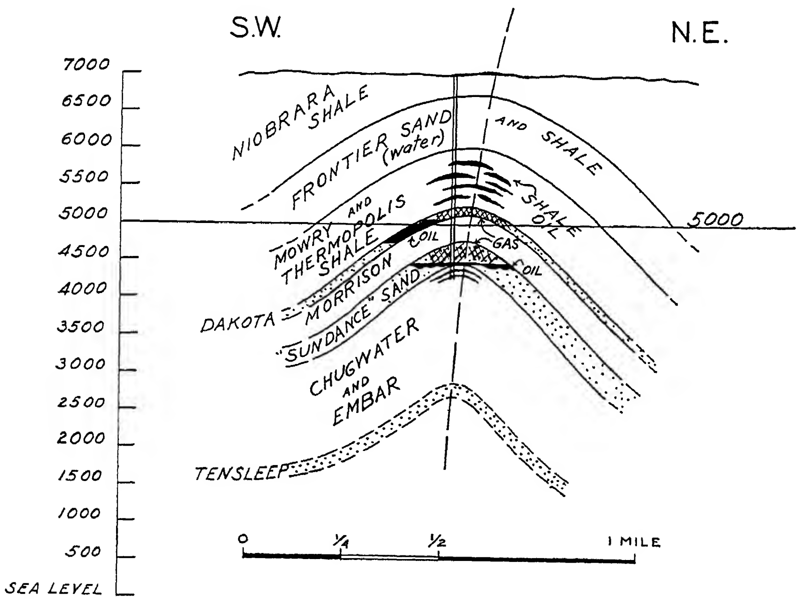

FIG. 7.—Section southwest-northeast through Ferris dome. Same vertical and horizontal scales. Depths in feet.

The closeness of the folding introduces some thickening on the crest; thus, the interval from the top of the Frontier to the top of the Dakota becomes 1,500 feet, an increase of 100 or possibly 200 feet.

If Ferris dome is faulted, the surface cover conceals the evidence. It has been rather closely drilled along the axis, yet the subsurface data indicate little or no faulting, certainly none of any magnitude.

Production.—The main sand members of the Frontier formation at a minimum depth of 290 feet carry water but no gas or oil. The thin and more or less lenticular sand members of the lower Frontier yield showings of gas and oil.

The shallowest commercial oil production comes from the Mowry shale and the sandy beds in the Thermopolis shale at depths ranging from 1,200 to 1,700 feet. As there are no sand members in the Mowry, and the oil does not seem to occur at definite horizons, it is assumed that it occurs in pockets and fissures produced by the intense folding of the brittle, siliceous shale. A rather persistent oil-producing horizon composed of approximately 5 feet of sandstone or sandy shale, 140 feet above the Dakota sand, is assumed to be the Muddy sand.

The Dakota and the Lakota sands, scarcely separable at Ferris, carry gas along the crest of the fold, surrounded by a very narrow ring of oil. Since the annular oil zone is only 200–300 feet wide and is somewhat variable as to position with respect to the contours, it is difficult to locate and drill wells that will not enter either the gas or the water. Three gas wells at Dakota sand elevations of 4,800, 5,028, and 5,180 feet, respectively, went automatically to oil or became oil wells on being drilled deeper into the sand.

Wells deepened to the Sundance sand, at depths ranging from 2,400 to 2,600 feet, have been disappointing, as both gas and oil production was small.

The Chugwater and deeper formations have not been tested, but a well now drilling has the Embar and Tensleep formations as objectives. The Tensleep should be reached at a depth of 4,100 feet.

As a field, Ferris has always been unimportant, and gives little promise for the future. The oil wells are characteristically small, average less than 100 barrels, and the gas wells soon became exhausted. Total production of oil to April 30, 1927, was 378,831 barrels. The American Petroleum Institute estimate of future production as of January 1, 1926, was 100,000 barrels, at which time 346,946 barrels had been produced.

The total gas produced to December 31, 1926, all from the Dakota sand, was 1,517,022,000 cubic feet, from an area of approximately 200

acres. The gas wells are now practically exhausted and are for camp use only.

MIDDLE FERRIS

Structure.—Two separate structural closures occupy the anticlinal area between Ferris and Mahoney domes. The easternmost of these, known as Middle Ferris dome, is adjacent to Ferris dome and is separated therefrom by a shallow syncline which limits the independent closure to 200 feet. This syncline is revealed by dips observable in pits dug in the shale at the few places not covered by sand dunes. A few strike and dip observations in pits, together with the records of the three gas wells, afford the only basis for determining the structure. The arrangement with respect to Ferris is *en échelon.* An *en échelon* arrangement with respect to West Ferris dome is also suggested by subsurface data, but the data are scarcely yet sufficient to control the contours fully in this locality.

Both surface and subsurface data are inadequate to indicate presence or absence of faulting.

Production.—The Frontier and all other sands above the Dakota are barren.

Two gas wells in the Dakota sand, at a depth of 2,300 feet, and with an initial pressure of 800 pounds per square inch, had produced 1,816,-880,000 cubic feet, in addition to considerable loss, from 1921 to December 31, 1926, at which time the pressure was 220 pounds per square inch. The remaining well of the three on the structure is a gas well in the Sundance sand. It had an initial pressure of 1,065 pounds and produced 1,043,-370,000 cubic feet of gas during 1925 and 1926, at which time the pressure had dropped to 675 pounds per square inch.

The gas area in the Dakota sand was probably not more than 160 acres. The gas area in the Sundance sand is more than 300 acres and less than 500. No oil has been found under the gas; and if any exists, the amount is probably small.

WEST FERRIS

Structure.—West Ferris dome is entirely concealed by soil and sand. Its crest was determined by interpolation and the first well, No. 1, in Sec. 29, T. 26 N., R. 87 W., thereby located. Six subsequent wells proved the correctness of the first location and permitted the drawing of controlled contours, except at the east end. The west end of West Ferris dome is separated from Mahoney dome by a structural saddle which may be faulted. The strikes and dips, together with the subsurface data strongly suggest the presence of faulting; but in the absence of direct evidence of faults, only the symbol for a conjectural fault is given on the map.

probable that closed structure should exist somewhere along the concealed fold; accordingly, during the summer of 1927 five diamond-drill holes were put down in Sec. 2, T. 25 N., R. 88 W., with the hope that reverse (west) axial pitch might be found. The correlated cores proved that the axis had been correctly located but that there is a continuous eastward pitch; therefore, no closure at the locality. There is no probability of reversal west of the cored area because of east dips observed in Sec. 34, T. 25 N., R. 88 W., and the fact that the structure must rise materially to reach the crest of Sherard dome.

The east end of O'Brien Springs fold possesses 500 or 600 feet of structural closure, as determined from a survey of the upper Steele sand rim rock and two transverse sections, one drawn at the apparent structural saddle in Sec. 2, T. 24 N., R. 87 W., and the other through the Ohio Oil Company's dry hole in Sec. 5, T. 24 N., R. 86 W. When, however, the curve representing the Dakota sand, 6,000 feet below the Steele sand, is drawn in on the two transverse sections, it is found that the closure practically disappears. This is caused by the fact that in the easternmost section the folding is more acute and the thickening of the 6,000-foot interval to approximately 6,600 feet practically nullifies the closure determined graphically in the Steele sand. Although the structural control thus established is necessarily not precise, it would seem that there is little probability of adequate structural closure on the Dakota sand; consequently, little inducement to drill a well 4,500 feet deep to test this sand.

Unfortunately, the three unsuccessful wells drilled by the Ohio Oil Company on O'Brien Springs anticline do not conclusively test the structure. The first well, located in Sec. 5, T. 24 N., R. 86 W., is very near the crest, but the depth of 3,205 feet was not sufficient to reach the Frontier sands. A very good showing of oil was reported at a depth of 1,612 feet, which should be in or near the G. P. sand. Well No. 1, Sec. 2, T. 24 N., R. 87 W., encountered a flow of gas in one of the lower Frontier sands but did not reach the Dakota sand because of mechanical difficulties. Well No. 2 in the same section reached the Muddy and the Dakota sands and found them barren. The two wells in Section 2 are not favorably located, as they are in the structural saddle which limits the closure in the exposed beds.

SHERARD DOME

Sherard dome is almost entirely covered by sand and soil and can be mapped only by means of projection of rim-rock data and by well records.

That the crest is in Sec. 14, T. 25 N., R. 89 W., in the vicinity of the Producers and Refiners Corporation well, where the Dakota sand rises

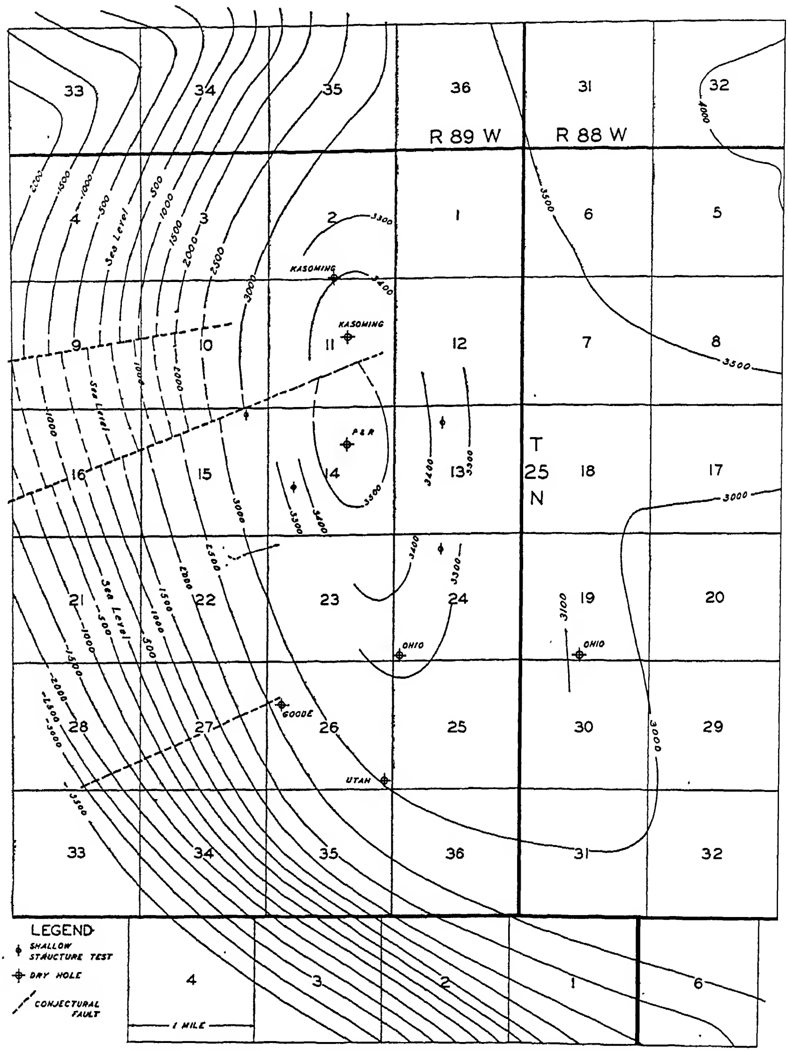

FIG. 8.—Structure of Sherard dome, contoured on top of Dakota sand. Datum, sea-level.

to an elevation of 3,596 feet above sea-level, is now well established. The only essential feature now undetermined is the depth of the structural

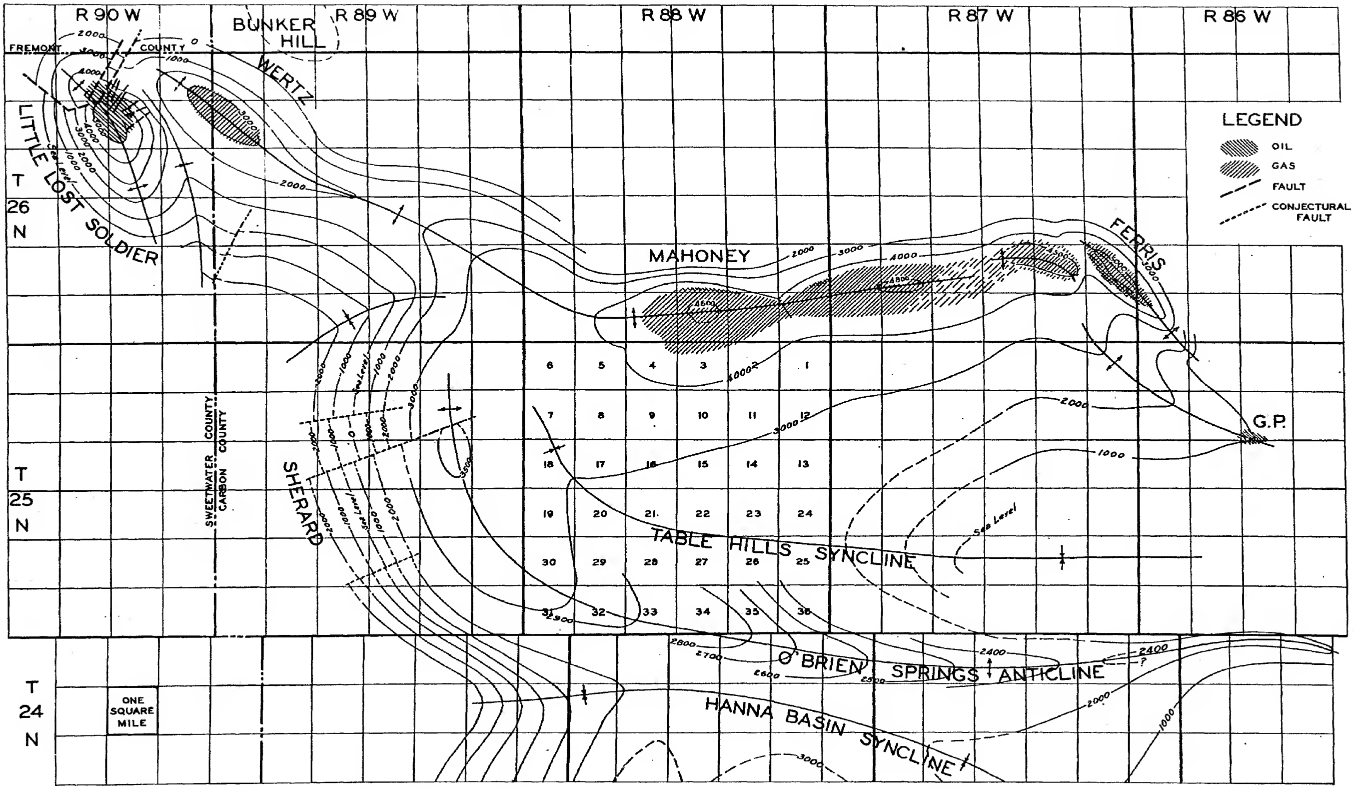

FIG. 9.—Structure of northern part of Lost Soldier district, Carbon, Sweetwater, and Fremont counties, Wyoming, contoured on top of Dakota sand. Datum, sea-level. Contour interval, 1,000 feet.

saddle between Sherard and Mahoney domes. Upon the depth of this saddle depends the amount of closure on Sherard dome. Even now it is evident that the depth of the saddle cannot be great and the closure therefore not large. The G. P. sand serves as a shallow key horizon here; and its depth in Section 12, T. 25 N., R. 89 W., if determined by a few test holes, would indicate the amount of closure.

Seven wells, of which five tested the Frontier and two the Dakota sands, prove the absence of commercial oil and gas in these sands. These wells, together with four shallow structure-test holes drilled by the Ohio Oil Company, control the structure contours in the central, covered area.

Immense flows of fresh artesian water from both the Frontier and Dakota sands indicate vigorous artesian circulation; consequently, unfavorable conditions for accumulation and retention of oil and gas. Showings of gas and oil were encountered in some of the sand members of the Frontier formation, particularly in the lower thin and lenticular sands which would naturally be less affected by the flushing action of artesian circulation; but such circulation in the main prospective sands, induced by inadequate closure and by gentleness of closing dip, is the most obvious reason for barrenness.

Because of the almost total absence of exposures within the Mesaverde rim on Sherard dome, there is no opportunity to observe fault criteria or other details of structure. Even the rim of more or less resistant sandstones has been largely removed by erosion and is now marked only by widely separated monadnocks in the shape of short hogbacks and cones. Recognition of definite horizons in these outcrops is difficult; but failure of certain horizons to join in a smooth curve because of apparent offset, when location, elevation, strike, and dip are considered, strongly suggests faulting somewhere within the covered area between the outcrops. Such more or less conjectural faults are represented on the map by lines composed of very short dashes. Faulting is also suggested by subsurface data in the vicinity of the Kasoming and the Producers and Refiners wells in Secs. 11 and 14, T. 25 N., R. 89 W. In general, however, the status of faulting is indeterminate on Sherard dome.

Although the Frontier and Dakota sands carry water, the writer is of the opinion that the Sundance sand at an estimated depth of 2,500 feet is a fairly favorable prospect for oil and gas. The principal reason for this belief is the fact that the Sundance is a finer, tighter sand than the Dakota and should be less subject to artesian flushing. The chances for Sundance oil and gas would appear even more favorable if the closure were augmented by structure tests in Sec. 12, T. 25 N., R. 89 W.

BUCK SPRINGS STRUCTURE

The Buck Springs structure is a half-dome in the Cretaceous formations, its crest located in Sec. 29, T. 23 N., R. 88 W. The Cretaceous strata, with the lower chalky member of the Niobrara at the surface, dip southwest, west, and northwest from a crest; and the whole is downthrown against the Tensleep, Amsden, and Madison formations of Carboniferous age.

In the hope that the fault planes were tight and that they would thus effect closure on the east, a well was drilled which tested the Frontier, Dakota, and Sundance sands and found them barren or filled with water. The well was located approximately 1,200 feet west of the fault scarp, but it was impossible to avoid all faults. The interval from the Frontier to the Dakota was 500 feet short in the well, which indicated that one important fault, or possibly more, had been penetrated. As it would be necessary to remain on the down-dip side of all faults of any consequence in order to expect oil and gas accumulation, the test was inconclusive, but the prospect is not very attractive for further exploration.

BELL SPRINGS (SEPARATION FLATS) DOME

The Bell Springs dome is a structural closure 500 feet in height, with its crest in Sec. 6, T. 23 N., R. 88 W. The west flank is marked by the steeply westward-dipping Mesaverde sandstone escarpment. The south closure is indicated by dips in the uppermost Niobrara. Evidence of the syncline which limits the closure on the east is seen in Sections 8 and 17. The north closure and the entire crest area have been determined from well records.

The structure is highly faulted, probably much more intricately than the meager exposures indicate. The faulting is largely longitudinal and seems to be the northern terminus of the Rawlins fault zone.

A well close to the apex of the dome, in Section 6, found gas and water in the Dakota sand at a depth of 1,920 feet. Several other wells lower on the structure found water in the Frontier and the Dakota sands. The deepest well on the dome found a good showing of oil in the Mowry shale, but all sands down to the lower Sundance or upper Chugwater were water-bearing or barren. The Tensleep sand at an estimated depth of 4,100 feet may contain black oil, but the depth is discouraging.

SOURCE OF THE OIL AND GAS

The Mowry, Thermopolis, and upper Dakota shales are dark colored and visibly organic, and it has long been known that oil can be distilled

from the Mowry beds. The laterally continuous and rather uniformly porous sandstone members nearest these organic shales are the Dakota and the Lakota sandstones which lie below them, and these are, to date, the principal productive strata. Oil and gas derived from the Mowry, Thermopolis, and upper Dakota shales, therefore, reached the Dakota and the Lakota sands by downward migration. The Frontier sands, excellent reservoirs though they are, carry oil and gas nowhere in the district, except the oil at Little Lost Soldier and a very small gas pool at Wertz. Evidently the lower Niobrara and lower Frontier shales in contact with these sands do not contribute oil and gas to them. The oil in the Frontier sands at Little Lost Soldier is easily explained by migration from the Dakota sands, along faults which are known to effect intercommunication between these sands. It seems probable that the oil and gas in the Sundance formation was also derived from the same source by downward migration, since it is less probable that it was derived from the Chugwater "Red-beds" or that it migrated through them from below. The Sundance, however, is composed in part of fossiliferous marine shales and limestones, and it is possible that these beds have furnished all or a part of the oil and gas in the Sundance sands.

SUPPLEMENTARY NOTE

Developments since the completion of this article in November, 1927, make necessary the following correction.

1. Recent core drilling indicates the presence of a north-south anticline, possessing the Rawlins Hills structural influence, in that locality situated between the southeast end of Sherard dome, T. 24 and T. 25 N., R. 88 W., and the west end of east O'Brien Springs anticline, Sec. 1 and 2, T. 24 N., R. 87 W. The extension of the east-west O'Brien Springs anticlinal axis across this area as shown in Figure 9 is therefore incorrect.

2. Several hundred barrels of oil accompanied by water discovered in the lower Embar formation or upper Tensleep sand on Ferris dome had a gravity of 36 degrees. It is possible that commercial pools of high-gravity oil occur on other structures in the Lost Soldier district.

RÔLE OF GEOLOGIC STRUCTURE IN THE ACCUMULATION OF PETROLEUM[1]

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ABSTRACT

This paper is intended to summarize and correlate the results of the papers included in the two volumes that comprise the symposium on geologic structure held by the American Association of Petroleum Geologists. The examples of various types of structure that are cited are drawn largely but not entirely from the symposium. Although, on casual reading, many of the papers may seem to depart in some particulars from recognized structural principles, petroleum geologists are not misled by the seeming "exceptions" into supposing that conditions really conflict with the principles. Careful studies have proved that the accepted relationships of oil and structure prevail universally, subject to the control of other fundamental criteria. The advance of our science during the last few years emphasizes the existence of many factors that were formerly unsuspected, any or all of which may affect the position of oil on, or in relation to, favorable structural areas. Every so-called "exception" is found to clinch the structural principles more firmly than before, and we can go forward with greater confidence despite seeming difficulties and can more keenly appreciate the pitfalls and the means for avoiding them.

I. INTRODUCTION

Any generalization as to the importance of geologic structure based upon a study of specific fields may be considered by some persons as having limited application and its utility may be gauged erroneously by the number of fields considered, even though all the individual writers on those fields may have arrived at definite and correct results in their respective fields of activity. However, this seeming weakness in a generalization may be made its source of strength.

In a discussion of the geologic structure of American oil fields we are confronted by the fact that they are of many different geologic ages, which range from Ordovician to Quaternary. Moreover, American structural conditions, although not so complicated, perhaps, as those of Poland and Persia, are multifold in their nature. Thus, American fields are admirably qualified to serve as world-types. Our present point of view is also governed by several other factors, as follows:

[1] Presented by title before the Association at the Fort Worth meeting, March 21, 1929. Manuscript received by the editor, July 9, 1929.

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1. This paper is written with the object of summarizing and correlating results of the papers included in the symposium (Vols. I, II[1]) on geologic structure held by the American Association of Petroleum Geologists.

2. The fields considered in the symposium are believed to be fairly typical of those which exist in their respective petroliferous provinces.

3. The fields considered are among those on which enough surface and subsurface data are available to enable their writers adequately to interpret them.

4. The papers are written by authorities on the geology of the respective fields.

5. Some of the more abnormal types of oil occurrences considered lie in states which have only recently come into public notice as oil producers.

Since the paper is written for the definite purpose stated, the examples quoted are drawn mainly from the symposium. The vast array of structural evidences that have appeared in geologic literature during the last quarter of a century could not be adequately considered here. Therefore, literature of outside derivation is, in general, only referred to in so far as it is important for the purpose of completeness or to avoid attaching undue weight to certain counteracting inside evidences. Neither is the paper intended as an exhaustive commentary on all references that are found in the two volumes on any particular phase of the broad subject. It is in no degree intended as an index, for only typical examples have been selected for each phase of the rôle of structure.

Although the importance of structure is stressed throughout the symposium, an effort was made to emphasize such other phenomena as also influence accumulation. These may be porosity, cover, hydrostatics, hydraulics, degree of metamorphism, tectonics, migration, regional sedimentation, periods of folding, unconformities, paleogeographic factors, faulting and fracturing, genesis, source of origin, etc., any one of which may be worthy of a symposium in itself. In particular we should understand that "structural accumulation" is not synonymous with "anticlinal (or domal) accumulation." Another point that the reader must bear in mind is the difference between surface structure and subsurface structure as determined for any particular stratum. The writers appear to have fully elucidated these differences.

[1] Volume references in text of this paper refer to this book, *Structure of Typical American Oil Fields.*

This paper is written in a foreign country,[1] where the writer's technical library is not available; hence he begs the indulgence of his professional confrères for any omissions of credit in references to the literature. It would not be practicable to mention all of the sources that have proved useful in the study; and still less would it have been possible, in the present effort, to study or to refer to all pertinent papers that have been written. The writer takes especial pleasure in acknowledging the helpfulness of Sidney Powers in reading the preliminary draft of the manuscript, making numerous comments, and supplying information on various localities. Thanks are also due to John L. Rich, F. H. Lahee, and other geologists for helpful suggestions. In addition, the writer's appreciation extends to the entire geologic fraternity for the abundance of existing information pertinent to the rôle of structure.

2. RELATIVE IMPORTANCE OF STRUCTURE AMONG ACCUMULATION CRITERIA

Statement of fundamental criteria.—The three or four criteria necessary for oil accumulation that were recognized a generation ago have been supplemented from time to time by others, so that there are now no less than eight criteria that may be considered fundamental, all of which must be applied and satisfactorily met if a locality is to be considered geologically favorable. We are here concerned mainly with proved fields of commercial value, and not with minute or sporadic oil deposits in rocks of many classes, ages, types of structure, and modes of origin. Two years ago the fundamental criteria for commercial oil occurrence were classified (25)[2] as follows:

FUNDAMENTAL CRITERIA FOR OIL OCCURRENCE[3]

1. Are the rocks of sedimentary origin?
2. Is the age of the strata (in part at least) similar to that of oil-field strata in some known oil or gas field?
3. Does a possible source of origin exist? If this be not apparent, may it nevertheless be present?

[1] Mr. Clapp's foreign address at the time was 68 Quai d'Auteuil, Paris XVI, France.—EDITOR.

[2] Number references in text of this paper refer to list of references at end of paper.

[3] "Surface indications" or seepages are here omitted, for, although they constitute a criterion, they are not a necessary fundamental of the accumulation or occurrence of oil.

4. Do porous beds or "reservoirs" exist in which oil may be held in commercial quantity?
5. If so, does sufficient "cover" exist above the reservoir beds to prevent the oil or gas from escaping to the surface and being lost?
6. Are the strata so slightly metamorphosed by heat or pressure that the oil has presumably not been driven out?
7. Does "geologic structure" exist suitable for concentrating oil in commercial quantity?
8. Are the hydrostatic conditions such as will not prohibit the accumulation of oil in pools?

Importance of structure as a criterion.—In considering the numerical order in which the structural criterion (No. 7) in the table should be ranked, we may start with the axiom that structure is *one* of the criteria for the accumulation of oil. A matter of equal certainty is that undue weight must not be attached to the existence of suitable structure; for, in the absence of a satisfactory accord with the other fundamental criteria enumerated, oil in commercial quantities will not be found. The question we should all ask ourselves, in general and as applied to every individual geological problem, is *exactly what* relative importance to assign to structure; for "an anticline in a petroliferous province is not the sole desideratum" (Vol. II, Prefatory Note).

Importance of structure variously gauged.—Doubtless the question would be answered in various ways by men working in different fields as well as by those concerned at different stages in the development of any particular field. For instance, structure as a criterion may be of greater relative importance to oil accumulation in the Rocky Mountain fields than it is in Oklahoma, and it may be of greater relative importance in Oklahoma than it is in Ohio. Structure may be of the most obvious importance in the early days of the development of a certain oil field; yet a stage may be reached during its development at which wells can be safely located within certain defined limits without the aid of structural geology. Still later, the utmost geological care may be necessary when locating edge wells in order to avoid their falling outside oil-bearing limits.

Necessary thoroughness of structural studies.—For these reasons each geologist must answer the question of the relative importance of structure in his own way. But he cannot avoid the conviction that structure is of great importance in oil accumulation and that it must be adequately considered at some stage in the field studies. Not only must the geologist consider the structure, but its multifold aspects must be taken up, point by point, section by section, contour by contour, until the most minute

details are given their proper application. The geologist must know the surface structure, the subsurface structure, and their relationship. If there are productive sands of more than one subsurface attitude, the respective structural surfaces must be considered in detail and all predictions must be based thereon. No phase of structure or of structural methods or reasoning may be safely omitted from attention.

Purpose of this paper summarized.—Thus far the field geologist is ahead of the generalizer; for structural details are nowadays commonly deciphered rather accurately, yet we are still asking some of the fundamental questions that were propounded in the early days of the profession. For instance, we may reasonably ask, What is the *relative* importance of structure? How can we properly evaluate certain structural phenomena? How do the so-called "exceptions" affect the structural theory? and so on. In other words, To what point has the profession advanced quantitatively? Doubtless every geologist and every geologic staff have found answers to such questions in specific fields of endeavor. Let us here make an effort to arrive at answers that can be applied more widely throughout our activities.

3. PERTINENCE OF STRUCTURAL CLASSIFICATIONS

When a geologist is studying any one of the great variety of structural types that produce oil, it is clear that he should hold in mind, consciously or otherwise, some sort of classification of favorable structures. The classification of the writer, originally proposed in 1910 (19) and published in full in 1917 (22) is here revised and somewhat abridged to include only the known commercial and semi-commercial fields. The classification, though often quoted in the past, seems also essential to the present paper.

CLASSIFICATION OF OIL AND GAS STRUCTURES[1]

I. Anticlinal structures
  a) Normal anticlines
  b) Broad geanticlinal folds (or "regional uplifts")
  c) Overturned folds
II. Synclinal structures
III. Homoclinal structures
  a) Structural "terraces"
  b) Homoclinal "noses"
  c) Homoclinal "ravines"
IV. Quaquaversal structures or "domes"
  a) Domes on anticlines
  b) Domes on homoclines and monoclines

[1] Simplified for use in present paper.

c) Closed salt domes
d) Perforated salt domes (or "*diapir*" structures)
e) Domal structures caused by igneous intrusions

V. Unconformities

VI. Lenticular sands (on any type of structure)

VII. Crevices and cavities irrespective of other structure
a) In limestones and dolomites
b) In shales
c) In igneous rocks

VIII. Structures due to faulting
a) On the up-thrown side
b) On the down-thrown side
c) Overthrusts
d) Fault blocks (or *horsts*)

The investigator need not accept this classification, for others may be of equal merit; yet some complete classification should be borne in mind during any investigation of field conditions. It is probable that newly discovered classes and subclasses of structures will continue to be added from time to time as the science of geology progresses. Thus, in the opinion of the writer, a classification is so helpful that it ought to be worked out in greater detail than the one quoted rather than less thoroughly. The present paper is not intended to be either an elaboration or an exhaustive commentary on the structural classification, but it is intended to stress some of the common types of structure and their related geologic features.

4. ANALYSIS OF A FAVORABLE STRUCTURE

Constituent parts of a favorable structure.—It is convenient to bear in mind the distinction between the various parts or elements of a favorable type of structure. For instance, an anticline or a dome ordinarily has an axis, a crest, flanks, and closure. The last-named element is considered the most important with respect to oil accumulation. Some of the structural features that occasionally modify a simple "structure" are faults, symmetrical and asymmetrical forms, etc.

Related structural features.—Closely associated with the elements which compose producing structures are certain underlying and adjoining features, without which the structure might be barren; for example, regional structure, subsurface manifestations of various types, and the adjoining synclines.

This "anatomy" of a structure, as it might be called, results in the application of different names for the broader groups of favorable struc-

tures, as in the anatomy of animals, plants, or minerals. Thus, if the structure be domal, it may be either a dome on an anticline, a dome on a homocline, a salt dome ("closed" or "perforated"), or a dome penetrated by or underlain by an intrusive igneous mass. An anticline may be a strong feature standing alone, one associated with alternating synclines, one of the broad geanticlinal type, an overturned fold, or a faulted anticline.

Other structural types.—Again, on homoclines, oil may be found on noses, in structural "ravines," on terraces, or (again) on domes. In any of the existing types of favorable structures oil may be associated with an unconformity, or with faults, or occur in crevices, pores, or cavities (varying in nature according to the different lithologic types). In addition there are the anomolies—oil in synclines, intraformational folding, and other misleading features. The rôle of all of these must be inquired into. Inasmuch as so many elements are allied with geological structures in the broad sense of the term, no wonder exists that the oil operator required decades to become convinced that oil accumulation is based upon definite principles and that it is not merely "where you find it."

Scope of the discussion.—The functions (or rôles) of the different types of structures on which oil is common are now generally recognized by oil geologists, but it seems necessary to comment on these functions as applied to the structures covered by the symposium and other favorable structures the world over. Only the principal types can be adequately discussed here. The reader should understand throughout that the statements, unless otherwise noted, refer to the structure of the top of the producing stratum and not to any surface rock form. The differences between surface and subsurface forms will be elucidated.

5. ESSENTIALS OF ANTICLINES AND DOMES

Definition.—Many geologists consider any arch in the strata—whether long or short, open or closed—as an anticline, and the literature seems generally to justify such usage. In the writer's structural classification (Art. 3)[1] an anticline was considered an upward arch that is considerably longer than wide and that is "closed" horizontally in all directions. In these days of specialized structure we need no longer refer to all uplifts or upward folds as "anticlines" without qualification, for anticlines and their related structures have been given different names to accord with their respective forms. Again, we need no longer avoid the use either of the term "anticline" or of "dome" to designate subsurface (buried) anticlinal or domal structures (Art. 6); for many subsurface

[1] Article references indicate subdivisions of this paper.

structures are anticlinal or domal where no confirmative surface structure exists. Almost any sort of structure may be found beneath a surface structure.

Closure and structural relief.—Anticlines and domes (as the terms are used in this paper) may collectively be called "closed structures," and the writer prefers to limit these terms to structures that are closed, unless qualifying words are affixed. In analyzing a closed structure we may logically ask what parts or elements of it are structurally essential and what their respective proportions may be of the anticlinal or domal area. But, in doing so, it is found that the size or proportion of any structural element has little importance.

For instance, some surface structures in Oklahoma, Kansas, and Ohio have such slight relief as to be barely distinguishable in refined survey work; and, in cases in which structure of oil sands themselves has been determined by careful subsurface studies, the relief may be correspondingly small. The Francisco pool of Indiana (Vol. II) has only 40 feet of subsurface closure. That of the Morrison field of Oklahoma (Vol. I) ranges from 40 to 150 feet, according to the particular sand under consideration (Figs. 2–5).[1] The closure of the Cromwell sand of the Cromwell field (Vol. II) amounts to only 70 feet (Fig. 3). On the contrary, the total closure in the Elk Hills field of California (Vol. II) is 450 feet (Figs. 4–6), and the closures of six producing domes in northwest Colorado (Vol. II) range from 400 to 1,200 feet (Figs. 2–8). Closure observed in some of the domes in the Big Horn Basin of Wyoming is from 1,000 to 2,000 feet, and the Little Lost Soldier field in that state (Vol. II) has at least 3,500 feet of closure (Fig. 1). The Ordovician relief in the El Dorado field of Kansas (Vol. II) is approximately 800 feet (Fig. 5), although the surface closure in that field is only 150 feet.

Similarly, the vertical relief of production on structure is also notably variable. Production may descend a dome only 60 feet from the crest, as at Fairport, Kansas (Vol. I) (Fig. 3), or it may descend many hundreds of feet, as in the Salt Creek–Teapot Dome field of Wyoming (Vol. II) (Fig. 1) and the Ventura Avenue field of California (Vol. II) (Fig. 5). The absolute heights of closure and relief seem to have little relation to productivity. And, as is shown in Article 7, production may exist in structures which have no closure whatever.

Rate of dip.—When oil was first discovered in the Appalachian region most geologists supposed that only structures of moderate dip would be

[1] Figure references in text throughout this paper refer to illustrations in papers cited.

found productive. When oil was discovered in the West in structures having 45°-90° of dip, these were believed to be exceptions to the general rule. It is now known that oil may exist in structures having any degree of lateral dip. And, although in oil fields of Paleozoic strata the dip ordinarily attains only a few degrees from the horizontal, this may not be a universal rule.

Age of folding.—So far as the present writer is aware, the importance of knowing the age of folding of any structure on which predictions are to be made was first emphasized by Hintze (41) some years ago and the subject has not been pursued intensively; yet it deserves recognition. Furthermore, the structure of a field may have been greatly modified by repetitions of folding along divergent lines. Moulton considers (Vol. II) that the structure of Pennsylvanian strata in the Martinsville pool on the La Salle anticline of Illinois is "principally the result of renewed deformation in post-Pennsylvanian time in areas subjected to important pre-Pennsylvanian folding." He declares that the principal uplift in that region has a trend slightly west of north, but that the "local fold on which deep production is found has a northeast trend and makes an angle of about 40° with the trend of the regional uplift." Similar examples may be found in the Mid-Continent fields.

It would be interesting to map the alignment of the major axes of subsurface domes in proved oil districts and to study their variations from normal. Such a study would doubtless bring out the fact that many of the subsurface "trends" are quite different from those of surface folds and that the subsurface trends more commonly parallel the pre-existing mountain ranges or other tectonic lines than they do the more recent surface alignments. A significant fact may be the common passing of folds into faults at depth and the arrangement of these faults in fairly regular systems.

6. RÔLE OF ANTICLINES AND DOMES

Importance of anticlines.—After four decades of petroleum geology the anticline remains a cynosure to an oil geologist in regions where the other necessary fundamental conditions prevail; and, when drilled, an anticline ordinarily rewards its discoverer by proving productive. A majority of the world's great oil fields are still found on anticlines or associated with them or with structures that may be considered "species" of anticlines—domes, terraces, noses, and fault structures. Therefore, in considering the fields covered by this symposium, we must first inquire to what extent production is anticlinal in a strict sense of the word.

Some typically anticlinal fields.—Some readers may be surprised that only a minority of the fields are acknowledged without qualification to be strictly anticlinal. Hertel describes (Vol. II) the Ventura Avenue anticline of California as an ideal anticline—"a sharp and well defined fold" with perfect closure on which a great oil field is situated. And, in the words of Pemberton (Vol. II): "The structure of the Elk Hills is a smooth elongate dome" in which it is "obvious that accumulation of oil and gas is induced by anticlinal conditions." Roberts explains (Vol. II) that the Long Beach field (the greatest field in California in point of total production to date) is also definitely anticlinal (Fig. 1). The Salt Creek (Vol. II), Rock River (Vol. II), Grass Creek (Vol. II), and Lance Creek (Vol. II) fields of Wyoming and the Elk Basin field (4) of Wyoming-Montana are perfect anticlines; and Harrison tells us that as many as nine sands are productive on the Grass Creek "dome" alone. The symposium also includes the Little Lost Soldier, Wertz, Mahoney, West Ferris, Middle Ferris, and Ferris "domes" of Wyoming (Vol. II)—the last mentioned five of which lie on a long anticlinal axis (Fig. 9).

That oil and gas accumulation in northwestern Colorado is "caused by anticlinal structure" is shown by Heaton (Vol. II) for the Iles, Moffat (or Hamilton), Thornburg, Rangely, White River, and Hiawatha "domes." Yet, some structurally perfect "domes" in the same region are barren, owing to causes not fully established. Weirich (Vol. II) reminds us that the Cushing field of Oklahoma (third among the fields of the United States in total production to date) derives its oil from as many as eight sands and that it coincides with a continuous anticline more than 20 miles in length, domed at Dropright, Drumright, and Shamrock. The Fairport field of Kansas (Vol. I), according to Allen and Valerius (Fig. 4), and the Saginaw field of Michigan (Vol. I), according to Carlson (Fig. 1), lie on anticlines.

In recent oil-field history the Yates field, the geology of which is elaborated by Gester and Hawley (Vol. II), is an excellent example of anticlinal occurrence in "an elongate eccentric dome."

Some typically domal fields.—No definite distinction can be made between anticlines and domes, for these types of structure generally differ only in degree. Thus, some of the anticlinal examples previously noted have been termed by some geologists anticlines, although others have called them domes. Acknowledged examples of productive domes are the more numerous, however, for this type of structure is common on the west-dipping Mid-Continent homocline and in many parts of the world

within and without petroliferous provinces. The accumulation of oil on domes was originally discussed comprehensively in 1912 (21).

Among the many typical domes that are productive in Oklahoma, the Garber field, described by Gish and Carr (Vol. I), is typically anticlinal (Figs. 3–5). The fields in the Turkey Mountain limestone (Vol. I) of that state are domal, according to Ruedemann and Redmon (Figs. 1–6). The Morrison field (Vol. I), described by Carpenter (Figs. 2–5) typifies numerous fields in the northern part of the state, and Burton describes (Vol. II) the Hewitt field (Fig. 2) as typifying some of those of southern Oklahoma.

Among the Kansas fields described by Thomas (Vol. I) those of Elbing, Florence, Covert-Sellers, and Peabody (Fig. 2) are domal accumulations. The Coffeyville field, sketched by Foster (Vol. I), lies on a well-defined dome (Fig. 1), both with respect to the gas-producing Oswego limestone of Pennsylvanian age and the oil-bearing bed—the upper Ordovician "Siliceous lime." Beekly (Vol. II) shows us that the Virgil pool (Fig. 2) is a dome "which makes a perfect trap for oil accumulation and is undoubtedly the governing factor in the concentration of oil."

Typical productive domes are not limited to one state, or two, for Nowels (62) shows (Figs. 1, 2) that the Rattlesnake and other fields of New Mexico are confined to domes. Those fields of Wyoming and Colorado which are not definite and acknowledged anticlines are generally recognized as coincident with domes of great magnitude. In a less productive state, Lusk claims (Vol. I) that the Tinsley Bottom field of Tennessee is located on a well-defined dome.

In the Permian basin of West Texas the Big Lake pool, described by Hennen (Vol. II), is closely coincident with defined domal structure in the Texon (discovery) and lower productive sands, and structural principles are further adhered to by the encircling of the pool by "edge water" in various sands. (Edge water is generally present in pools even where not mentioned.) It is significant that the deepest well in the world found its fourth oil zone, in which gas having rock pressure of about 3,000 pounds per square inch occurred with the oil, at a depth of 8,520 feet. Referring to the Petrolia field, Kendrick and McLaughlin (Vol. II) tell us that "there is probably not a more perfect example, in that part of the country, of geological structure being the cause of accumulation of oil and gas."

Anticlinal or domal plunging fields.—It need not be inferred that the perimeters of all of the previously named anticlinal and domal fields correspond with a definite closing contour or that the edge-water line sustains

exactly the same elevation throughout the perimeter. The essential generalization is that the fields are anticlinal or domal.

One step removed from fields that conform almost exactly with a definite bounding contour drawn on a producing sand, or fields that depart from the ideal condition in such slight degree as to excite no comment, are those where the structure is an ideal one but the productive area plunges in one or two directions. For instance in the Lance Creek field of Wyoming, Emery describes (Vol. II) a structural closure of 600 feet where the "position of gas, oil, and water in the Dakota sands . . . . is in accordance with the anticlinal theory of accumulation." Yet, in this field (Fig. 1) "both the gas-oil line and the water table plunge toward the northeast, with the result that production of both gas and oil extends much farther down structure in this direction than it does elsewhere on the anticline." In the Rock River field (Vol. II) the edge-water line plunges nearly 900 feet from one end of the field to the other (Fig. 1). Most fields exhibit this tendency to a minor degree. In a large field in which intense artesian pressure combines with a high degree of friction owing to limited pore space we should not expect that the edge-water line will correspond with the same structure contour on all sides of the pool.

Anticlinal occurrence influenced by porosity.—Opposed to the unquestionably anticlinal and domal fields, already described, are those in which the accumulations, definitely related to favorable structure, are controlled by porosity of the sands. The subject of porosity is discussed in Article 11, but a few examples of its influence are given here for the sake of continuity of discussion.

Edwards and Orynski's paper (Vol. I) indicates that porosity constitutes an important accumulation factor in the Westbrook field of Texas, which is situated on a long, low, and irregular fold. Davis explains (Vol. I) that the production of the Artesia field of New Mexico (Fig. 2), situated on the apex and southeast flank of a northeast-trending anticline—although "an orthodox case of anticlinal collection"—is accompanied by "a few anomalies that are prejudicial to this conception," for the oil fills sand lenses that are irregularly distributed on the fold (Fig. 2).

The Bradford field of Pennsylvania and New York, which is widely known on account of the success of artificial water-flooding, and in which eight sands are productive of oil or gas, is commonly supposed to be independent of geologic structure. Nevertheless, a comprehensive paper by Newby, Torrey, Fettke, and Panyity (Vol. II) indicates, by means of the subsurface structure of the Bradford sand, "two asymmetrical anticlines

trending northeast and southwest, plunging southwest and converging on the northeast in a broad dome. The closure exceeds 150 feet." Thus, anticlinal occurrence in the Bradford sand is conspicuous, although accumulations in other sands have been influenced to some extent by the lensing of several sands (Fig. 2) which coincide only in part with the structural "high."

Anticlinal occurrence influenced by hydrostatic conditions.—The question has frequently been raised why certain domes of the Rocky Mountain region—apparently as good structurally as some others that are eminently productive—yield no oil or gas commercially but only large volumes of water. In the region surrounding the Big Horn Mountains, for instance, little fluid except water is found in the belt of domes first removed from the mountains; yet many oil fields are found in domes of the second line. The question has been answered in the past, and the possible explanation is repeated here in the words of Irwin (Vol. II) (describing the Sherard dome north of the Lost Soldier district):

> Seven wells, of which five tested the Frontier and two the Dakota sands, prove the absence of commercial oil and gas in these sands. . . . . Immense flows of fresh artesian water from both the Frontier and Dakota sands indicate vigorous artesian circulation, consequently, unfavorable conditions for accumulation and retention of oil and gas.

The conditions mentioned are typical in domes closely related to the mountains, but are not so common in those situated farther within the bounding geosynclines. There can be no doubt that the prolific production of some fields (of which Yates, Texas, may be an example) (Vol. II) is due to their great hydrostatic head; yet in more fields the gas held and compressed in the sand is the principal expulsive force, as shown originally by Beal and Lewis (7) and recently explained by Miller (55).

Anticlinal occurrence variously influenced.—Several other influences control the position of oil and gas on favorable types of structure. The fields of Kay County, Oklahoma, though repeatedly in the past mapped as associated with the well-defined anticlines, furnish evidence that production is not coincident with the structural crests everywhere and in all sands. The abnormal features are explained by Clark and Daniels (Vol. I) as due to the following circumstances:

1. In the Burbank sand of the Mervine field (Fig. 4) and in the "Mississippi lime sand" of the Ponca field (Figs. 5, 6), due to buried topography of a pre-Pennsylvanian hill of "Mississippi lime" over which the structure has been formed.

2. In a part of the Tonkawa sand production of the Ponca field, "due to the irregular nature of the upper part of the sand body."

3. In the Neva limestone of the Blackwell and South Blackwell fields (Figs. 7, 10), probably due to differences in porosity in the limestone that forms the reservoir rock.

As an example of the general adherence of the fields of Osage County, Oklahoma, to structural principles, influenced by various factors, is the pool (Vol. II) on the Cold Spring anticline of T. 25 N., R. 8 E. In this field a slight agreement exists between surface structure and the subsurface structure of the three productive sands; but such similarities do not exist in all Osage fields.

As an illustration of a still different type of accumulation control, Collom indicates (Vol. II) that the Lompoc, Santa Maria, Casmalia, and Cat Canyon fields (Fig. 1) of Santa Barbara County, California, are "in cross-faulted anticlines," despite the rather peculiar relations and character of the diatomaceous Monterey shale.

Anticlinal occurrences in miniature.—Miniatures of domal structure—pimples on a great homoclinal dip—seem to be responsible for the Tri-County field of southwest Indiana (Vol. I), where the productive structures range in area from a few acres to 160 acres or more. Esarey thinks lenslike sand bodies may be responsible for the arching of the overlying rocks in those fields. With respect to the Francisco pool, covering less than a square mile of area, Moulton shows (Vol. II) that the accumulation of oil "is governed by structural conditions in accordance with the anticlinal theory." In the Sumner County fields of Tennessee local flexures covering a square mile or two, superposed on the northeast flank of the regional Nashville dome (Vol. I) "have determined the location of the oil." Similar minor pools are common in Ohio and elsewhere.

Relation of the origin of domes to productivity.—At this stage of the discussion we may inquire what must be the origin of domes inside a petroliferous province in order to assure production. Many articles, enumerated by Stephenson (Vol. II) favor conflicting theories of domal origin as regards the northeast Mid-Continent oil and gas region. Some productive Oklahoma domes have evidently been formed by lateral pressure. Others have originated through "differential settling" of sediments over ancient land masses, as proved by Blackwelder (9) and Thomas (Vol. I), long buried mountain ridges in Kansas and Oklahoma (Art. 10). This theory of "gravitational compaction on the structure of sedimentary rocks" has been emphasized by Hedberg (38), Bridge and Dake (11). The theory has been studied by Nevin and Sherrill (59), who conclude that "a

compaction fold has in it certain inherent characteristics which are sufficiently different from those of any other type of folding to make it recognizable." Vertical movement may account for some domes, as is favored by Spooner (Vol. II) in the case of Homer and by Crider (Vol. II) for the Pine Island deep production of Louisiana. Certain other domes have been formed by intrusion of salt masses, and still others may be due to igneous intrusions.

Relation of subsurface structures to production.—In most of the early structure contour maps of public and private geological surveys the mapping was done exclusively on the basis of surface observations. Data were not at hand for the preparation of subsurface maps, and the widespread discrepancies in attitudes of the various sand surfaces was not recognized. It is now customary to map the structure of every producing or possibly producing formation individually.

Thus the relativity of subsurface structures must always be taken into account. Levorsen (Vol. II) shows that all pools of the "Greater Seminole district" of Seminole and Pottawatomie counties, Oklahoma, "are producing from anticlinal structures, many of which are reflected in the surface formations as minor folds, flattenings, and change of strike." These fields, in the order of their production to January 1, 1929, are Seminole City, Earlsboro, Bowlegs, Little River, St. Louis, Searight, Pearson Switch, Mission, and Maud. The Seminole accumulations (69), on a broad regional saddle between the Ozark and Ouachita uplifts, are due to doming (Fig. 4); but the entire Seminole "uplift," both regional and local, is a subsurface manifestation quite contradictory to the surface structure. Langworthy tells us that oil in the Cromwell sand of the Cromwell pool (Vol. II) is distributed in fair conformity to subsurface mapping. The subsurface relationship is influenced by "the erratic condition of the sand body, which in at least two places grades laterally into limestone. . . . ." Production would have conformed perfectly with the structural features had erratic sand conditions not been encountered. The Depew pool, reviewed by Martin (Vol. II), is an example of many small Oklahoma pools having similar subsurface domal relationships in more than one sand (Figs. 4, 5).

Again, in the Kevin-Sunburst field of Montana, Howell (Vol. II) writes (Fig. 3) that, although there is "no production on top" of the great subsurface dome, nevertheless "a study of the map indicates that local structure in areas of porosity has a decided effect on accumulation." This writer acknowledges that "factors other than structure which have affected accumulation are amount of porosity and nature of contact zone,

as well as the unconformity itself and a variable condition of water saturation." The effect of unconformities on the discordance between surface and subsurface structure is explained in Article 10.

Even in Wilbarger County, Texas (Vol. I), where little relationship is evident between surface structure and oil occurrence, subsurface mapping by Fuqua and Thompson (Fig. 3) indicates that the production from Pennsylvanian sand lenses in the Landreth, South Vernon, and smaller pools coincides closely with subsurface domes. Relative to subsurface conditions in the adjoining Stephens County fields, however, Esgen declares (Vol. II) that

> the accepted theories of accumulation of gas, oil, and water on structure have been fully verified by development . . . . although sand conditions modify the theoretical structural location of accumulation in the Strawn, and the characteristics of the Bend limestone influence to some extent accumulation in the Bend.

Esgen points out that the greatest oil accumulation on the Bend arch—Breckenridge field—lies on "a subsurface structure with almost 200 feet of closure, which covers an area of approximately 25 square miles" and that the greatest gas well in the history of that county was found on the highest part of the structure. Other pools on the Bend arch (as Ivan, Curry, North Caddo, and Hart), although not strictly anticlinal, are related to plunging subsurface anticlines. In the adjoining Eastland County fields ("Ranger fields") (Fig. 1) little anticlinal relationship is apparent, although the Desdemona pool lay on a definite "high." The widespread accumulations on the great Bend arch should be borne in mind in connection with Article 12.

Among foreign fields the oil accumulation at Comodoro Rivadavia (97) in Argentine shows an almost perfect coincidence with anticlinal "highs," even though the structure is not apparent at the surface; and, in the absence of geophysical mapping at the date of discovery, the oil could not have been discovered in advance of drilling.

Rôle of salt domes.—Lest any reader apprehend that an important class of producing structures, so common on the Gulf coast and in Utah, was omitted from adequate attention by this symposium, the writer points to the article by Carlton (Vol. II) on the West Columbia dome of Texas as being representative of salt domes as a whole. Doming is produced by upward-moving salt masses at the intersection of faults or planes of weakness. Although salt domes are essentially domal, the structural relationship on any particular dome is largely controlled by porosity, "trapping" incidental to salt contacts, and other strictly local features, to such an extent that ordinarily only one quadrant of a domal area is pro-

ductive. "Oil accumulation on salt domes is either in supercap sands, cap rock, or lateral sands," all of which are structural in their attitude; and Spindletop is an example of a field with all three types of production. The West Columbia field, however, produces from lateral sands exclusively (Figs. 5–8).

Cautions relative to salt domes.—The fact that salt domes are commonly found in regions having no appreciable topographic expression has nothing to do with the generalizations concerning them. Moreover, nobody should suppose that all structures which contain salt are "salt domes." Many wells in West Texas, Kansas, and Ohio pass through salt beds, yet the doming is not of the "salt dome" type. In Egypt, salt in the form of more or less continuous beds has been found to underlie large areas and not to be limited mainly to domes as in the case of true "salt domes."

A serious mistake would be made in supposing that all producing structures in a salt-dome country or state are "salt domes." This is evident in Louisiana and Texas. Again, just as the Caddo fields of northern Louisiana are quite different in structure and origin from the salt-dome fields of the Gulf Coastal Plain, so in Persia a distinction should be recognized between the anticlinal fields of the west and southwest (Art. 14) on the one hand (in which highly folded salt beds are actually present) and the "salt domes" of the extreme south of the Persian Gulf region (not yet proved commercially productive). Even at Gemsah, Egypt, referred to by some geologists as a characteristic salt-dome field, the salt, gypsum, and anhydrite were seen by the writer to have been mildly compressed into structures similar to the "flow zones" of western Persia rather than to have been the primary cause of doming. The other Egyptian structures seen by the writer evince no similarity to salt domes, but carry beds of salt which are comparatively little disturbed.

Pertinence of geophysical methods.—The use of geophysical methods in locating salt domes is now well known and has attained a higher degree of success than with any other type of structure. Lest any skepticism remain on this subject the writer calls attention to the discovery in the Gulf Coastal Plain of the United States during the last six years of more domes, through the use of seismographs, torsion balances, and other geophysical devices, than were known in the same petroliferous province during the entire period previous to the advent of geophysics. In the year 1928 as many as thirty-three new salt domes were discovered by these methods in the Gulf Coastal Plain (96).

Structural accumulation important despite so-called "exceptions."—Inasmuch, therefore, as structures are of many types and are subject to

Schneider has shown (Vol. I) that the Urania oil of Louisiana, although found in a sand lens of which the position is defined by a "disconformable contact" is nevertheless situated on a slightly domed terrace (Fig. 5) on a monoclinal dip.

Thus, productive terraces are real features and are not rare. Although ordinarily thought of as limited to the United States, they will doubtless be found, like other types of productive structures, to be productive also in foreign countries.

Attitude of terraces.—In the structural classification of the writer terraces were made a sub-class of homoclinal structure (formerly known as "monoclinal"). If, however, we imagine a terrace to be tilted or to have been tilted during or after accumulation of oil in such a way that its nose points upward and forward, allowing its flat upper surface to slope backward, we have an anticline or a dome. This thought, and especially the tectonic history, may be worth bearing in mind when trying to explain various inter-relationships of the oil, gas, and water found on terraces. Accurately mapped examples should be carefully studied to determine whether or not any definite principle exists for predicting the position of oil on any terrace that has been discovered.

Limitation of terrace productivity.—Although a fair proportion of so-called terrace accumulations may be due largely to the presence of sand lenses (Art. 11), yet structure appears to control accumulation to a certain degree and is therefore entitled to consideration. Judged by the many terraces in Ohio, both in surface strata and in subsurface sands (generally water-free in that state) and by the production of oil from a terrace in the Fort Payne limestone of Tennessee (Vol. I), terraces seem to be productive mainly from limestones and from water-free sands, but this hypothesis does not apply universally.

Definition of noses.—The writer has found no definition of "noses" as applied to a type of structure, but a definition may exist. At any rate, the term explains itself. So far as is known, attention was first called to this type of structure in 1911 (18), and in 1917 the term "monoclinal noses" was used (22), but noses may also lie on homoclines or anticlines. Bonine (9) recognized noses in central Ohio as favorable gas structures. The Stephens field of Arkansas (Vol. II) may be recognized as a typical example, mapped by Spooner for the Nacatoch sand (Figs. 3–5). Examples could be duplicated in Ohio, Kansas, Oklahoma, and Wyoming. Although some subsurface noses are actually productive, many surface noses are underlain at depth by anticlines or closed domes (Art. 10), so that the number of de-facto noses may be comparatively limited.

Homoclinal "ravines" ("monoclinal ravines" or "structural ravines").—The term "ravine" was first applied to a producing type of structure, so far as known, in 1911 (20). Structural "ravines" have exactly the same relation to an inclined sand surface that a topographic (surficial) ravine forms in a sloping hillside. At that time certain oil pools in the Clinton sand of Ohio were shown to be controlled by the existence of "ravines." As that sand is practically a water-free sand, the oil seems to have settled into these "ravines" or on the accompanying terraces in a way similar to the accumulation of synclinal oil (Art. 13) in West Virginia.

Competence of terraces and noses to trap oil.—Regardless of any fancied resemblance to anticlines or domes, terraces and noses appear competent to trap oil in either (*a*) water-free or (*b*) water-saturated sands, and thus they may result in productivity in sands of either group. The common occurrence of oil on terraces in regions of water-free sands may be (*a*) accidental, (*b*) due to porosity changes, (*c*) due to the fact that terraces form a more perfect obstruction to oil descending the dip (as it does in water-free sands) than to oil ascending; or, in saturated sands, (*d*) oil may be pushed upward and out of a terrace by water which exists in the sand under pressure. Evidently the chief function of a terrace is to act as a trap to upward- or downward-moving oil; and terraces, while often oil-bearing, are subject to all the non-structural influences which modify accumulation on domes and anticlines (Art. 6).

8. RÔLE OF FAULTS

Early conception of faults.—The rôle of faults, although still perhaps imperfectly known, was sadly misunderstood for half a century after the discovery of oil in the United States; and operators, believing faults to be dangerous phenomena, tried to avoid them. The popular superstition against faults was so strong that for years it permeated the geological fraternity, and many government and private reports recommended the avoidance of faulted structures. The absurdity, as we now understand it to be, was commonly expressed in the once-familiar words: "The country appears too much broken up."

Some examples of important faulting.—Although the precise rôle of faults has never been systematically defined, much has been written that touches on the subject. One thing is certain: that is, that we need not try to avoid them. In some places the existence of faults has actually been found favorable to oil accumulation. For instance, the Salt Creek–Teapot Dome field (Vol. II) of Wyoming and the Elk Basin field of that state and Montana (Vol. II) are traversed by innumerable faults, some of which

have hundreds of feet of vertical displacement, and some exceptionally productive wells are developed close by. The faults of Elk Basin field, the relative ages of the three distinct systems, their vertical persistence, relation to periods of folding, their origin, and relation to oil accumulations have been studied by Estabrook (30), Irwin (Vol. II), Washburne (87), and Bartram (Vol. II). The faults of the Salt Creek field have been discussed by Irwin, Estabrook, Wegemann (89), and Lewis (49), in addition to the present writer (23). Many of the Wyoming fields are notable for faulting; yet, strange to say, the Rock River (Vol. II) and Lance Creek (Vol. II) fields evince no faulting. The Turner Valley field of Alberta, Canada, is on a complex anticline cut by overthrust faults.

Some California and Colorado examples.—Proceeding to northwest Colorado, we learn that some faults on the Iles dome (Vol. II) have as much as 1,100 feet of throw; the largest one results in separating the structure from the rising structure to the south (Fig. 2); yet the conditions are not typical of other domes in that region, which evince little faulting. According to English (Vol. I), (25), faults may be considered responsible for the accumulation of oil at McKittrick, California; and Collum shows (Vol. II) that, in the fields of Santa Barbara County, the "movement and location of the oil" were influenced by cross-faulting. The Long Beach field (Vol. II) is shown by Roberts (Fig. 1) to be controlled on one side by a fault and fracture zone.

Normal faulting has been an important factor in controlling accumulation in the homoclinal sand-lens oil fields on the east side of the San Joaquin Valley, as in the Mount Poso (95), Kern River and Kern Front oil fields (33). In the latter (39)

> the oil was probably trapped by an overlapping condition and faulting which brought impervious shales and sands in contact under the proper conditions of oil accumulation. The areal extent of the field has probably been determined on the east by faulting, on the north and northwest by shore-line conditions which were not favorable to oil accumulation, and on the south and southwest by edgewater conditions.

Some Texas examples.—The fault systems bounding the Mexia belt (Vol. I) of central Texas are well known, and the Luling field (Vol. I) is bounded by a fault. McFarland states that, in the Laredo district (Vol. I), accumulation of oil and gas is found (*a*) against a fault which cuts a transverse fold and (*b*) where there is "a change of direction of the fault. In each condition, closure against the fault affords a suitable reservoir." In the Carolina-Texas field of Webb County (Fig. 2) accumulation is due to a faulted dome or nose extending throughout several square miles. A

similar explanation may prevail in the Henne-Winch-Farris field of Jim Hogg and Zapata counties (Fig. 6) and in the Randado field of Jim Hogg County (Fig. 7).

Some other examples.—In other states also faults are found in the oil fields. The Blackwell field (30) of Oklahoma is bounded by a fault (Figs. 8, 9) in the Mississippian and deeper series of strata. The "Wilcox" sand production of Tonkawa is trapped by an anticline, cut off by a fault. The subsurface structure of the Hewitt field (Vol. II) shows faults of several hundred feet displacement which were a factor in oil trapping. Faults are conspicuous in the Crinerville field (68). Among foreign fields, faults up to 160 feet in throw are found in the Panuco field (3) of Mexico; and, in the fields of northwest Peru (46) faults range from mere fractures to breaks of 5,000 feet vertical and 2 or 3 miles horizontal displacement. The Glenmary field of Tennessee is, according to Lusk (Vol. I), "a low faulted anticline."

Examples of increased production near faults.—As already stated, certain Wyoming fields have occasionally been shown by geological literature to have greater production near faults than elsewhere. This is notably true in the Salt Creek field. In a summary of conditions prevalent in the Lost Soldier district, Irwin (47) explains:

> The productivity of the structures, other factors being equal, is in close relation to the extent to which they are fractured and faulted. . . . . The more numerous and open the faults, the greater the tendency towards an oil pool or to barrenness through more or less complete leakage. The fewer and tighter the faults, the greater the tendency toward a gas pool or to barrenness through lack of migration and accumulation.

Tendency of faults toward radiation.—Faults may be of several types (strike and dip faults, longitudinal and transverse or cross faults, diagonal and radiating faults, normal and reversed or thrust faults, etc.). In the Homer, Louisiana, field (Vol. II) (Fig. 6), in the Wyoming fields, and in the Topila (or Paciencia-y-Aguacate) dome of Mexico (3) faults tend to radiate from the center of disturbance. This tendency is true to a less extent in the Elk Basin field of Wyoming-Montana (Vol. II). Such features may be due to torsion, for Stephenson (Vol. II) believes that most of the folds of Osage County, Oklahoma, are "the result of rotational stress, probably transmitted through the basement complex" and that the forces, "acted several times during geologic history on the same lines of weakness."

En échelon relations and origin.—The *en échelon* faults of Osage County (Vol. II) and elsewhere in north central Oklahoma may be due to torsion,

likewise, as is believed by Sherrill (79, 50). Lahee (Vol. I) suggests an *en échelon* or offsetting arrangement for the shallow-sand gas fields at Mexia and Groesbeck, Texas, and he postulates that arrangement for the fault belt as a whole. A similar arrangement of structures is exemplified by the position of the Nigger Creek field (Vol. I) to the west of and opposite the saddle between the Mexia and Groesbeck fields. Considering the question of origin, Lahee suggests that the Mexia and Tehuacana fault systems "were produced by torsional forces involved in the settling of the East Texas geosyncline." Charles and Page believe (18) that slight regional torsion movements in the rocks have produced joints.

Some examples of block-faulting.—Fault blocks have been little described in oil-field literature, but they exist in northwest Peru (46), in the unproved seepage areas of New Zealand (24), and in New Guinea. Even in Alsace, where oil occurrence is not commonly understood to be associated with structure, the most important accumulations seem to be on the upthrown sides of horsts tilted by faulting (34).

In the symposium, the Irma field of Arkansas is described by Teas (Vol. I) as a "faulted monocline lying against the south side of a graben" in which "the highest point of the structure lies along the fault, so that the fault is responsible for much of the closure." The displacement there is 325–470 feet, oil being found on the upthrown side. The Stephens field (Vol. II) is also closed by a graben (Figs. 3–5), but the fault, in common with nose structures in the same field, may or may not constitute the principal factor in the accumulation.

In the matter of dip, oil-field faults range from vertical, approximating the rule, to as low as 50° in an important fault of 500 feet of throw in the Homer field (Vol. II). Some faults may be horizontal (Art. 9).

Faults that are limited to strata at or near the surface.—Judging from Langworthy's studies (Vol. II) it is evident that some surface faults of the *en échelon* systems of north-central Oklahoma (Fig. 2) "do not carry down" through the producing sands. Levorsen (Vol. II) attests the same circumstance in the fields of Seminole County (Figs. 10, 11, 13, 14). The Depew pool (Vol. II) is overlain by similar surface *en échelon* faults (Fig. 2) which are not evident at depth (Figs. 3–5).

Faults that are limited to subsurface strata.—From what has been written concerning subsurface structures (Art. 6) it will be understood that very many faults do not reach the surface. Some of these faults grade upward into folds; others have presumably been formed previous to deposition of the overlying beds.

Examples are numerous. The displacement of the Woodbine (pro-

ducing) sand in the Nigger Creek field ranges from 500 to 550 feet, as opposed to surface faulting of only 260 feet. In the Cromwell sand of the Cromwell field of Oklahoma (Vol. II) a fault exists of 214 feet displacement (Fig. 3) which is not represented at the surface (Fig. 2); but, on the contrary, a quite different set of *en échelon* faults appears in surface mapping throughout several square miles of area.

The Luling field of Texas is mentioned by Brucks (Vol. I) as a subsurface structure in which "the major structural feature that controls the accumulation of petroleum . . . . is a system of N. 35° E.-trending, connected faults having the down-thrown side on the northwest." This field —7 miles long and ½ mile wide—might be considered a faulted homocline, for only at the south end is anticlinal structure apparent aside from that caused by fault closure.

Fault zones.—The geologic structure of the Mexia fault zone, elucidated by Lahee (Vol. I), had previously been described by Fohs, Robinson, Pratt, Hopkins, Hill, Sutton, and Pepperberg. The best known map of the Mexia field is that of Pratt (Lahee's Fig. 15), and the map of the Powell field (Lahee's Fig. 23) is credited by him to Hill and Sutton. All the fields of the Mexia zone have structural relations similar to those portrayed.

A long narrow graben, formed by the Mexia and Tehuacana zones of faulting, is repeated at intervals nearer to the Gulf of Mexico throughout seven or more counties. The Mexia, Groesbeck, South Groesbeck, Powell, North Currie, Richland, and Wortham fields were developed under regionally favorable conditions in the Mexia zone and the Nigger Creek and Cedar Creek fields were similarly developed in the Tehuacana zone. In the Nigger Creek field "the fault is not a single plane, but consists of a faulted zone which ranges from a few feet to 200 feet in width." Pepperberg states that "its closure in the subsurface structure at the top of the pay zone along the fault is due to drag," and the same opinion is expressed by Lahee for part of the Mexia zone. The last-mentioned zone "is a series of overlapping faults, all trending in a direction a little oblique to the trend of the zone as a whole" and all having "a downthrow to the west."

Relation of faulting to migration.—A matter that has occasioned much controversy is the question of migration. Although Lahee presents strong evidence against upward migration along faults in the Mexia region, Spooner (Vol. II) believes that the "erratic distribution of oil in the Oakes sand" of the Homer field is due to upward migration along a fault plane, and Teas (Vol. II) makes a similar suggestion with regard to Bellevue. There seems little evidence that faults are necessary to the migration of

oil from deep-lying formations into the sands where it is now found, for in West Virginia and Pennsylvania numerous sands are productive, one above another, in regions of no faulting.

However, Mills (56) has shown that "under favorable conditions, especially in firm consolidated strata, faulting that has yielded open fissures has been an important factor in the migration and accumulation of oil and gas" and that "the migration of oil and gas through fissures has been upward. . . . ." In some places faults have obviously permitted the ascent of oil from deep-lying sources, for seepages emerge from faults in Mexico, Persia, Wyoming, and elsewhere. Hennen (Vol. II) presents evidence of upward migration along a fault in the Big Lake pool of Texas. Irwin (47) considers it "reasonable to conclude that the openness of the fault planes at Little Lost Soldier" (Wyoming) "permitted the free migration of oil and gas from a lower source to the Frontier sands," and he gives evidence therefor.

Modification of former structural relations by faulting.—Another matter to bear in mind is that the once existing structural relationships may have been transformed through faulting since accumulation of the oil. According to an unpublished letter, O. B. Hopkins believes that at Negritos, Peru, "the oil was accumulated under hydrostatic head," but that later the structure was much faulted with the result that both water and oil were trapped where they had accumulated. "Oil is found in down-faulted as well as up-faulted blocks and the contained water is stagnant in the blocks where found." Another example is Pechelbronn, Alsace, where in the mine galleries concentration of the oil in gently dipping oil sands is found against faults with displacements of only a few inches.

Relation of faulting to anticlinal accumulation.—If, now, we analyze the examples of faulting that have been recorded, we find either that (*a*) the faults have modified the otherwise favorable structure without vitiating its structural functions as an oil trap or (*b*) the faults themselves have produced anticlinal conditions in certain sands, thereby causing oil to be trapped. Thus, faults must be recognized as a definite factor in the structural criterion of oil accumulation.

9. RÔLE OF OVERTHRUSTS AND OVERTURNED FOLDS

The most classic example of oil associated with great overthrusts, or "*charriages*" as they are called in Europe, comes from the Boryslaw field of Poland (81), where oil is found (*a*) on or near the crest of an overturned anticline, (*b*) associated with minor surface anticlines, and (*c*) directly underneath a great horizontal fault plane. A foreign field in which the writer

has seen overthrusts that may constitute an important factor in accumulation is western Persia and 'Iraq. These overthrust faults, shown by Nicolesco (61) (Fig. 35) after Richardson (78), may not extend to any great depth, and may be closely related to intra-formational movement in the surface strata (Art. 14).

The present writer fails to find any fundamental difference between an overthrust fault and an overturned fold, except that the first named has ruptured the strata instead of folding them; and it is obvious that folding and rupturing may exist together. The relation of oil fields to overthrust faulting is given little attention in the symposium, for the probable reason that American fields are seldom complicated by overthrusts. The best known example in the country may be at McKittrick, California (Vol. I). Oil in commercial quantity has not been found in connection with the Pulaski fault (17, 15) (a great horizontal overthrust) of southwest Virginia or with any other overthrust in the United States outside of California. Knowledge of structural conditions that underlie the overthrusts of the Canadian foothills is as yet imperfect, for the underlying anticlines appear to be quite distinct from those which have folded the beds overlying the fault plane. The study of overturned folds and overthrusts opens a wide field for investigation in world-geology as related to oil occurrence.

10. RÔLE OF UNCONFORMITIES AND RELATED FEATURES

Definition.—Unconformities are now known to be an important factor in the structure and accumulation of oil fields. We are not here concerned with innumerable irrelevant unconformities and disconformities that do not intercept any productive formation, do not cause appreciable angular divergence between the oil sands and overlying beds, and do not represent "buried hills" or old shore lines. The unconformities that are given consideration are those that in some way affect the position of the oil accumulations, that is, unconformities that may function as "traps" or may cause conditions leading to trapping, assuming that oil and gas exist in the rocks and that the other fundamental conditions are satisfied.

A few examples.—The importance of careful study of all unconformities is illustrated by Fletcher's paper (Vol. II) on the Caddo field of Louisiana, in which paper grave doubts are expressed concerning certain early correlations. Misunderstandings of conditions also existed in Oklahoma and Kansas before the days of subsurface studies of unconformities. It appears suggestive that the principal producing "sand" in the Kevin-Sunburst field of Montana (Vol. II) lies directly below the unconformable

erosion contact of the Madison limestone of Mississippian age and is the porous, eroded surface of that limestone, itself. According to Schneider (Vol. I) the Urania field (Fig. 3) lies on an irregular anticline 6 miles long and 2 miles wide, having 50 feet of closure, superposed on a terrace having an area of 24 square miles that underlies the Angelina-Caldwell surface flexure of Louisiana. In this case oil exists in a disconformable contact between the productive sand and the overlying formation. All of the "Wilcox" sand fields of Oklahoma have unconformities in the section. In addition to the American examples, unconformities have long been known in certain foreign fields; for example, the Maikop field of Russia (83).

Development of limestone porosity by erosion.—The most important type of oil reservoir in limestone is, according to Howard (43), one in which porosity has been developed by erosion previous to deposition of the beds which now overlie the reservoir. This type "probably involves fully 95 per cent of the total production from limestone." Murray (58) has explained that "almost every limestone field in Ohio, Indiana, Michigan, Kentucky, Ontario, and Illinois obtains its production from a reservoir which lies within 100 feet of an unconformity."

It is interesting to notice that the great fields of Persia and 'Iraq lie in the upper part of the Asmari limestone, mainly of Oligocene age, separated from the overlying beds by unconformity (61).

The same principle is acknowledged by Moulton (Vol. II) who, in referring to the Martinsville pool of Illinois, tells us that the "accumulation of oil in the Mississippian limestone was determined largely by the presence of elevations in the erosional surface on which the Pennsylvanian was deposited;" and he finds that "weathering processes in pre-Pennsylvanian time" have developed porosity that determines the rate and amount of production.

Rôle of "buried hills."—Within the last few years geologists have found that many of the best known oil fields in the Mid-Continent and some oil fields elsewhere overlie or adjoin prominent subsurface erosional ridges. The buried Nemaha Mountain range ("Granite Ridge"), parts of which have been often described, beginning east of Lincoln, Nebraska, extends south across Kansas, beyond Oklahoma City, and constitutes the best-known example of "buried hill" in the United States. This ridge controls oil accumulations in the El Dorado, Augusta, Oxford, Garber, Oklahoma City, and other pools (Vol. I) through trapping that is directly associated with the unconformity or on domes along lines parallel with it. Detail maps by Reeves (Vol. II) show that at El Dorado, the largest field in Kansas, the surface and Ordovician structures (Figs. 4, 5) coincide with a

complex of domes overlying the Nemaha Mountains. Another example is the buried Amarillo Mountains with superposed oil and gas fields (6, 66).

The earliest recognized example of a "buried hill" comes from the Healdton field in Oklahoma, in which the conditions were discovered by Powers (66) some years previous to the general acceptance of subsurface ridges by geologists. Burton explains (Vol. II) that the Hewitt field in the same region overlies a "buried hill," which has been described (71) as lying on the north rim of a buried southeast extension of the Wichita Mountain system on which the Duncan, Healdton, and Hewitt fields have been developed. At Crinerville (68), where the ancient land mass is only partly buried, the Pennsylvanian accumulation lies near an ancient shore line which existed in all the sands. The Petrolia (Vol. II), Nocona, Electra, and adjacent fields of northern Texas also overlie "buried hills." It has been suggested that the "Tamasopo ridge" of Mexico and certain structures in the Maracaibo Basin and elsewhere in Venezuela may be of similar derivation. On the east side of Lake Maracaibo the prolific oil sands disappear up dip by lensing.

Accumulation of oil may be in or above buried hills or at the unconformities within the section. Many buried hills have been rejuvenated several times or else have not subsided during sedimentation as rapidly as the surrounding areas. In the fields along the buried Nemaha Mountains and at Cushing oil and gas are found above and in the buried hills, but the best production is obtained from the top of the Ordovician hills or from sands resting at the unconformity. Healdton (4) production comes from a thick sand series which abuts small Ordovician limestone peaks covering only a few locations, but over most of the field the sands are separated from the limestone by shale. In the fields along the buried Amarillo Mountains, gas occurs in or above granite wash on top of buried granite hills, and oil occurs in this wash and also in porous limestones on the flanks of the hills which are characteristic of the plains type of folding as defined by Powers (71).

Shortening of columnar sections over anticlines.—Aside from their rôle as oil "traps," unconformities are now considered by some geologists as having world-wide importance because a majority of anticlinal fields manifest shorter columnar sections than those in the synclines bounding either flank. For instance, the "Siliceous lime" is only about 350 feet thick over the crest of the El Dorado anticline (Vol. II) of Kansas, though normally 1,000 feet thick in the surrounding country.

Shortening of columnar sections is not universally due to unconformities, for uplifting of a structure may have gone on simultaneously with

deposition. For example, this is quite apparent in a study of the domes in the saliferous basin of Transylvania. Nevertheless, where shorter sections appear in drilling an anticlinal structure, an unconformity may be postulated. Upward tectonic movements which produced the dome or anticline may also (*a*) have resulted in producing an unconformity (if the action was sufficiently rapid), they may (*b*) merely have caused disconformity, or (*c*) the strata may thin so imperceptibly in approaching the fold that either term may seem inapplicable.

Many writers comment on this greater thickness of strata on the flanks and in the adjoining synclines than on the anticlinal folds themselves. Thus, Snow and Dean (Vol. I), referring to the Rainbow Bend field of Kansas, declare: "On the south and east sides of the field the lime is 100 feet thicker than on the crests of the folds"; and, again, "A similar but not so pronounced difference is found in the Cherokee shale." Thomas (Vol. I) demonstrates considerable shortening of the section over the Elbing and Burns domes, and states that "the Cherokee shales appear never to have been deposited on the tops of these folds." Sections across the Winkler and Yates county fields of Texas are said to give enormously greater thicknesses of strata in the basins east and west of the "white lime" anticlines (algal reefs, in part) than upon them, the greater part of the thickening being due to variations in the percentages of anhydrite and salt. This fact is not substantiated, however, in "salt domes," in which the intruded, local salt deposits must be vastly thicker than in the surrounding areas where salt has not, in most places, been discovered by drilling. The importance of shortened sections over productive anticlines is only beginning to be appreciated.

General remarks on structural discordances.—The discovery of differences in structure between surface beds and those existing at depth now occasions no surprise among geologists; but in the early days of oil geology it was generally believed that sediments at depth would be found parallel with those at the outcrop and that discordant dips would only be found to the extent that formations might die out or thin out laterally. We might now almost assert that the opposite is true and that entire agreement between surface and subsurface dips is known to be the exception and not the rule.

Adherence to structural principles regardless of unconformities.—Unconformities do not refute the structural theory. They merely act as important controlling factors, as do faults. Unconformities in some places form a floor or margin on or against which the porous "reservoir" rocks have been deposited; and in other places the processes of erosion in the

production of unconformities actually cause the formation of reservoirs which are subsequently overlain by impervious beds. Unconformities cause angular divergence between surface and subsurface strata, thus embarrassing the field geologist; yet, when his work is completed, he finds that production adheres strictly to structural principles and the extent of the reservoir beds, modified by any local unconformable conditions that exist.

Summary.—The general discordance in dip between surface and deep-seated structures has nothing to do with the truth of the structural theory; for, whatever the surface structure of a locality may be, it is the subsurface that must constitute the criterion as to a favorable spot for the accumulation of oil. In the United States we more often find that the discordance existing in direction or degree of dip or in the position of anticlinal crests throughout any vertical sequence is due to (*a*) thinning of intermediate beds laterally, (*b*) unconformities or overlaps, or (*c*) contemporaneous folding.

The first-named type of discordance is exemplified by the thickening of the Ohio shales at an average rate of 40 feet per mile eastward across Ohio (20), revealing the deep-lying Clinton sand as quite different in structure from the Berea or shallow sand. The second type is illustrated by the well-known examples of overlaps on the west side of the San Joaquin Valley, California, as at Coalinga (1), and in the Sunset-Midway area (65). It is also illustrated by numerous examples of "buried hills" in the Mid-Continent fields that have been mentioned already. The third type of discordance, in which folding has gone on contemporaneously with sedimentation (Vol. II), is common in the Mid-Continent and Rocky Mountain fields of the United States. The best example known to the writer is in Transylvania.

II. RÔLE OF POROSITY AND LENTICULAR SANDS

Conception of porosity in sands and sandstones.—As one condition that affects the position of oil on a favorable structure in the presence of other suitable fundamental conditions is porosity of the sand, too few records have been published in the past (*a*) of actual porosities from which measured production was obtained and (*b*) of quantitative relations existing between production and porosity throughout any particular field. Geologists have generally assumed the porosity of producing sands as being between 10 and 30 per cent. Esarey, however, finds (Vol. I) the porosity of the Moorestown sand in southwest Indiana to be only 5 per cent. Hartnagel and Russell show (Vol. II) that representative porosities of six

samples from good producing wells in the New York fields range from 12 to 17 per cent. Melcher's investigations (54) reveal the ranges in porosity in typical fields as being from 7 to 19 per cent in Pennsylvania, 12 to 26 per cent in Wyoming, 12 to 39 per cent in Oklahoma, 7 to 35 per cent in Texas, and 14 to 41 per cent in Louisiana.

Conceptions of porosity in limestones.—Although in sands and sandstones it may be obvious that the oil reservoirs consist of the aggregate pore spaces between the sand grains, the mode of oil occurrence in limestone "pores" is not so apparent (Art. 10) and oil may occur in reservoirs of many types. Two samples of oil-saturated limestone from Archer County, Texas (Vol. I), were determined by Winn as having actual porosities of 13 and 16 per cent, respectively; yet limestone oil is not all found in pores between constituent particles. The theory that it is sometimes due to dolomitization is well known. As an indication of the multifold ways in which oil may exist in limestone, Howard's classification (43) based upon the origin of "porosity" deserves recognition.

As a corollary to Howard's classification may be mentioned the suggestion of Gester and Hawley (Vol. II), who consider that the porosity (ranging from capillary conditions to those "assumed to be almost cavernous") of the Permian limestone in the Yates pool of Texas resulted from "solution by acid waters." This would be in accordance with the accepted explanation of the method of formation of present-day limestone caverns.

Notable example of a pinching sand.—Since oil is ordinarily held in porous sandy beds, it evidently exists in places in lensing strata. Perhaps the most classic example of a great oil and gas field occupying the pinching belt of a producing formation comes from the Clinton sand of Ohio. Gas exists under wide areas in the up-dip (20) western feather edge of a great sand lens, whereas oil is found at places of structural interruption (terraces and "ravines") and suitable porosity somewhat down-dip from the general homoclinal structural slope east from the gas field. In the locality described by Bonine (10) the accumulation of gas due to disappearing lenticularity is merely modified by the existence of a local nose (Art. 7). For all practical purposes and discussion, the Clinton sand is considered as being water-free, although it contains some water in Vinton and Jackson counties (Vol. I).

Accumulations due to local lenticularity in Ohio and Pennsylvania.—With reference to the hundreds of low rolling folds and shallow basins in southeast Ohio, Lockett (Vol. I) tells us that "many of the structures have been proved to be the controlling factors of shallow sand accumulation, although as many more which looked as promising when mapped have

been dry." The same writer finds, along the Ohio end of the Burning Springs anticline, that "accumulation is the result of the general anticlinal structure, but is further controlled by sand conditions and by local structure which in any restricted area will be found to be a series of noses, terraces, and troughs, as a rule lacking any general trend."

The position of the oil accumulations is apparently due to lithology in the Cow Run sand of the Chester Hills field (Vol. I) of eastern Ohio, where Cottingham studied the structural conditions comprehensively enough to hazard the opinion that 65 per cent of the shallow sand production of Ohio has some structural basis. He does not, however, include the Clinton sand (the most important producing sand in Ohio aside from the Trenton limestone); and, since Clinton production (when considered in connection with its actual subsurface attitude and the lensing-out westward of the sand up-dip) is definitely structural (20), the percentage of Ohio production that has some structural basis must be considerably higher for the state as a whole than might be inferred from the studies of the shallow sands. Robinson (Vol. II) confirms the long accepted fact that the existence of local tight texture in sands of the Pennsylvania fields is "the cause of the dry holes drilled on otherwise favorable structure" and sometimes of "a very good well on one lot and a dry hole on the adjacent lot."

Some Kentucky examples.—Proceeding south to eastern Kentucky we find that, in the Lee-Estill-Powell County field (Vol. I) oil is contained in "porous lenses of a magnesian limestone." Fiske concludes that "while production is undoubtedly associated with major folding and faulting, its location is entirely controlled by the character of the pay horizon, production occurring where porous lenses are found in the limestone." With reference to the Campton field the conclusion is drawn that "the principal control of production in this field is the local character of the Corniferous limestone." The same writer concludes that, with reference to the Owsley County field,

although there is some doming and minor faulting, and a suggestion of a terrace at the gas field, there is no major fold . . . . and the folding does not account for the localization of production. Production here seems to be controlled entirely by favorable conditions of porosity in the reservoir rocks.

Again, in the Clay County gas field, production

seems to be associated with major folding . . . . localized by the character of the producing horizon.

Some Texas examples.—Writing of the southwest Texas fields (already mentioned in Article 8) McFarland states (Vol. I) that "faulting and sand

lensing are the principal factors of the accumulation of oil and gas in this district"; and he adds that "sand lensing is responsible for the accumulation in the Randado field and in the Cole sand of the Cole field. This sand lensing appears to represent an old shore line . . . .," nevertheless, the "accumulation is found along this line of lensing only where it crosses a broad transverse fold that has a northwest-southeast axis, thus affording closure against the lens." In the Smith-Ellis field of Brown County, Storm declares (Vol. II) that structure "seems to have been only an indirect cause of the accumulation of oil." He finds that porosity, percentage of siliceous content and thickness of the sand, rather than structure, are the controls of the amount of oil produced.

Some Oklahoma examples.—The structural theory of accumulation is not confirmed by Wilson's (Vol. I) cross section (Fig. 2), which indicates that, in so far as the Bartlesville (or Glenn) sand of Glenn pool, Oklahoma, is concerned, a sand-lens, pinching toward the east, has much more to do with the concentration of oil in that field than have domes; and, furthermore, other domes to the south and west of Glenn pool contain no oil. Sands describes (Vol. I) the Burbank field as much like the Glenn pool in its structural relations and porosity control. The Wilcox sand oil deposits in Glenn pool are, however, closely related to favorable subsurface structure, as is characteristic of Wilcox pools elsewhere in the state. Still another example of lensing sand is found in the Crinerville field (68). The relations of sand lenses in the Henryetta district (73) have been elucidated by Reed (Figs. 1, 2) by representing graphically the variations in thickness of a certain sand.

Some Kansas examples.—Lenticular production is also illustrated by Snow and Dean (Vol. I) in a description of the Rainbow Bend field of Kansas (Fig. 1). Production in a sand at the base of the Pennsylvanian series is said to be "controlled almost entirely by the character and extent of the sand body," with only seeming relations to domal or anticlinal structure (Fig. 2).

Other examples of lenticular oil accumulation.—Referring now to the Stephens County field of Arkansas, Spooner (Vol. II) tells us that the structural "high" "may have been the factor that determined the accumulation" in the area, but that "the distribution of the oil" was determined "by the character of the reservoir sand, chiefly by its lenticular structure." Differences in the degree of cementation and the proportion of argillaceous material in any sand are, of course, factors in the porosity. Even at Elk Hills, California (Vol. II)—an obviously anticlinal field—the sand conditions "influence the volume of production more than posi-

tion on structure." In the Martinsville field (Vol. II) of Illinois the "dips in the Pennsylvanian are so gentle that it is difficult to determine whether the structure was as important a factor as sand conditions in causing oil accumulation." Again, although some of the New York oil is definitely synclinal, Hartnagel and Russell state (Vol. II) that, for the most part, the sand pinches out beyond the oil-producing limits "as in structures of the lens type" (Figs. 3, 4). It is evident that, although lenticular production is widespread in its distribution, it is generally related to structure.

"*Shoestrings.*"—Closely analogous to pinching or dying-out sands are lenses that take the form of "shoestrings," "golden lanes," etc. The best-known examples are found in Kansas, where they were first called to attention by Rich (75). They were later discussed by him in other papers (76, 77). The Madison "shoestring" has since been critically studied by Cheyney (Vol. II) with similar results, and some work on "shoestrings" has been done by Cadman (16). All these writers agree that the sand lenses described are independent of structural geology; and are of varied origin, such as shore-line deposits (including sand bars and delta bars) and possibly valley fillings.

Similarly, in Oklahoma, Lewis has shown (Vol. II) that the Delaware Extension pool (Fig. 1) evinces conditions similar to the "shoestring" pools of Kansas, but that the "occurrence of the sand strongly suggests a buried river channel, which possibly flowed from northwest to southeast into the main Nowata-Chelsea pool." Lewis likens the sand conditions also to the Chesterhill streak in the Cow Run sand of Ohio and West Virginia, and he states that "like the Chesterhill streak, the Delaware pool has channels of thick, loose sand winding throughout the pool, being first on one side and then on the other side of the sand body."

According to Thompson and Hubbard (Vol. I) the oil of Archer County, Texas, is found in sand bodies, something like "shoestrings," "which have been deposited on the axes of relatively low structures." The presence of sand on these high areas and its absence in the synclinal areas is thought by those writers to be due to the advancing of a shallow sea over a series of low folds partly represented by topography, causing material to be eroded from the low hills and redepositing the sand and heavier material in shallow water "while sand and silt would eventually sink in the deeper water."

Writers on "shoestrings" have shown (16) (Vol. II) that, where oil or gas exists in sand lenses having local changes in thickness, the structure contours determined for the lenticular sands may not always give the true deformation, but instead they show only the shape and extent of the

sand body. In cases of this sort the field geologist should consider whether to contour (*a*) the deformation or (*b*) the top of the sand.

"Shoestrings" have seldom been reported from outside the United States; yet there is no reason why they may not exist widely. An example of a 15-mile long and spotted "shoestring," seemingly of the valley type, comes from the Nephtiana-Shirvanski field of the Maikop district in Russia.

Some abnormal types of porosity.—Some of the abnormal types of productive structure consist of serpentines and other altered igneous rocks, reported responsible for the semi-commercial field at Havana, Cuba, and the field at Thrall, Texas. The Lytton Springs field was described by Collingwood and Rettger (27), who have shown that production comes from the upper 200 feet of "an old, buried, volcanic cone"; and, as its contour is essentially domal (Plate 32), although mushroom shaped (Fig. 3) it does not depart essentially from structural principles. Another abnormal but commercially unproductive type was seen by the present writer in the Mexican fields (22), where asphaltic oil is flowing down the side of a basalt plug from an included breccia 50–100 feet above the surrounding plain. The oil is presumed to enter the basalt through fissures that connect with the productive sedimentary strata directly adjoining. Abnormal types may continue to be found as the science of geology progresses, but the purpose of the present paper will not be served by exhausting their discussion.

Adherence to structural principles despite porosity differences.—Thus a vast array of evidence points to porosity as one of the fundamental conditions that affect oil accumulation on otherwise favorable structure. Like faults and unconformities, lensing sands do not refute the structural theory, but they support it when the geologic relations of oil, gas and water are carefully studied with reference to any restricted area. Oil and gas are trapped in the saturated sands in the highest structural levels of suitable porosity accessible to fluids, whereas in water-dry sands the oil must exist synclinally, allowing gas to fill the sands at sufficiently porous spots almost anywhere higher in the porous stratum.

12. RÔLE OF "REGIONAL STRUCTURE"

Definition.—Some persons have supposed that "regional structure" is more important for oil accumulation than are local structures, but this view does not seem to be justified by experience. Regional structure is certainly one cause of the existence of certain production districts, such as the Arbuckle-Wichita-Amarillo mountains of Oklahoma, the Bend arch

and the Red River uplift of Texas, the Cincinnati arch of Ohio-Indiana, the Nashville dome of Tennessee, and the La Salle anticline of Illinois. Many fields have been discovered on similar "regional structures"; yet fully as many fields seem to lie on the adjoining homoclines if not in the actual geosynclines.

Regional structural basins are of equal importance because many oil fields are found near their margins and some farther within them.

Some examples of "regional uplifts."—The importance of "regional structure" is evident from the discovery of the Seminole uplift, which carries upon it the Earlsboro, Searight, Seminole City, Bowlegs, Little River, and other pools in Seminole and Pottawatomie counties, Oklahoma. The fact that the surface rocks overlying the uplift have a quite different structural attitude has nothing to do with the theory or fact of oil accumulation (see Art. 6), for the oil-bearing beds lie in the subsurface uplift and follow the principles of the structural theory.

As to Texas, the close coincidence of many fields with the Bend arch (Vol. I, p. 306, Fig. 1) has been discussed in many papers and is here affirmed by the contribution of Esgen (Vol. II), who declares: "The great Bend arch presents a magnificent structure for the accumulation of petroleum." Like the Seminole uplift, the Bend arch is mainly a subsurface manifestation. The Red River "uplift" is another regional structure which consists of a chain of disconnected Cambro-Ordovician limestone and "granite" hills extending from Cooke County on the east into Foard County on the west, a distance of approximately 200 miles. Kendrick and McLaughlin (Vol. II) tell us that "the Petrolia dome would never have existed had it not been for the Red River arch" and that the "structure was the direct cause of the accumulation of petroleum" in that field. Gester and Hawley explain (Vol. II) that the Yates field constitutes "a marginal fold on the southwest flank of the geosynclinal 'Saline basin' of West Texas and is evidently the southeasternmost 'closed' fold on that same line of regional uplift traceable northwest through the Crane County and the Upton County fields" as illustrated in Figure 1 of Hennen (Vol. II).

All of the fields of northwest Louisiana (Vol. II) are situated at structurally favorable places on the regional Sabine uplift. The Homer and Cotton Valley fields lie on prominent domes (Fig. 1); whereas in the Caddo, Pine Island, and Hosston districts, which have their own restricted structures and modifying conditions, the oil is concentrated in numerous local pools.

Similarly, the Cincinnati arch is a "regional uplift" (surface and sub-

surface) that controls the existence of the fields of northwestern Ohio, northeastern Indiana, and southwestern Ontario. The Arbuckle-Wichita-Amarillo mountains control the existence of the Crinerville, Hewitt, Healdton, Duncan, Robberson, Cement, and other fields situated between and adjoining the Arbuckle and Wichita mountain mass collectively considered and the existence of the line of oil fields over the buried Amarillo Mountains. The Big Horn–Casper mountain uplift of Wyoming controls the existence of the Salt Creek–Teapot dome, Big Muddy, Poison Spider, and other fields situated between and adjoining Casper and the south end of the Big Horn Mountains.

Examples of regional structural basins.—The Big Horn Basin of Wyoming is rimmed by important oil fields (40); the Michigan Basin already has an oil field on each side; and the West Texas structural basin as defined by drilling within the salt basin has oil fields on three sides (Vol. II). The San Joaquin, California, Basin is rimmed with oil fields. The Los Angeles, California, Basin has many oil fields within it as well as near its margins.

Summary.—The association of numerous productive structures with a single "regional uplift," or with the margin of a broad structural basin, is common. Thus, if a geologist discovers a new regional uplift (either surface or subsurface) in a petroliferous province, he may wisely concentrate attention upon it until localized favorable structures are found thereon. Yet, this does not mean that a favorable type of structure will necessarily be barren if it lies outside any "regional uplift."

13. SYNCLINAL OCCURRENCES OF OIL AND GAS

Synclinal oil and gas in Appalachian fields.—In West Virginia and eastern Ohio many structural "highs" are found to be barren. In the words of Davis and Stephenson (Vol. II):

> Even though West Virginia is the state where the anticlinal theory received its earliest practical application, later developments have proved that the state also contains the outstanding examples of synclinal oil pools. This is especially true in the southern part of the state, where such important synclinal fields as the Tanner Creek field of Gilmer County, the Rouzer pool and the recent Granny's Creek pool of Clay County, a part of the Blue Creek and Clendenin pools of Roane and Kanawha counties, and the Big Creek pool of Lincoln County are located. In the central part of the state the Copley field of Lewis County, and the Wolf Summit fields are the major synclinal fields. Some of the synclines are closed structures; others are open.

The Griffithville field is another definitely synclinal field described by the same writers.

In West Virginia the most important sands which produce oil from synclines are the Maxon, Keener, Berea, Big Injun, Weir, Gordon, Gordon Stray, and Fifth sands; these generally carry very little water. Where production is found on the flanks or the upper ends of synclinal basins or in the bottom of synclines, this occurrence is, strangely enough, like other seeming anomalies mentioned in this paper, consistent with the structural theory, as was long ago shown by Griswold and Munn (36); for the oil may be considered to have settled into the lowest structural position permitted by the low water levels existing in the particular sands in the synclines concerned. This condition of affairs was recognized in mapping by the West Virginia Geological Survey and recently illustrated by Reger (Vol. I) for the Copley pool (Fig. 5). The Wassons describe (Vol. I) the Cabin Creek field as a homoclinal accumulation in a thickened portion of the lower Berea sand well down on a synclinal flank. Since the Berea carries no water, the oil has been enabled to fill the sand as far down the homoclinal slope as the "pay" lens exists.

Although geologists familiar with other fields may contend that all anomalous structural relationships in Pennsylvania are due to the distribution of porosity in lenticular sands, this contention is not confirmed by observation. The distinction between saturated and water-free sands must be made; and, where made, the synclinal occurrences in the states mentioned are found due to the principles of the anticlinal theory.

Similar fields are described by Hartnagel and Russell, who state (Vol. II) that, where minor anticlinal and synclinal folds exist in the water-free sands of New York, the oil is found in the synclines. Robinson, also, in acknowledging the common occurrence of synclinal gas in Pennsylvania (Vol. II), shows that some accumulation is controlled by minor up-folds in the major synclines.

Synclinal oil in Oklahoma and elsewhere.—Synclinal oil is reported in a few pools in Osage County, Oklahoma, in sand lenses deposited around and between "buried anticlinal hills." The Ramsey and certain other small pools of Washington and Osage counties are perhaps examples (37) of this relationship. Possibly the West Virginia type of synclinal accumulation may be absent only because of the water-saturated condition of Oklahoma sands in general in contradistinction to their water-free condition in West Virginia and Ohio. The San Juan oil field of Utah is in a syncline and production comes from a water-free sand (57).

Anomalous synclinal accumulations.—The close analogy of the Florence field of Colorado (Vol. II) to synclinal occurrence will be referred to in Article 16. Another anomaly is found in Stephens County, Texas, where

a few synclinal occurrences exist which have not been fully explained, but Esgen (Vol. II) considers them important.

Suggested possible cause of absence of water.—The cause of the absence of water from West Virginia sands has remained a mystery. A possible cause of the water-free nature of sands in some synclines is suggested by Thom (82), who points out that regional unloading of a great land mass through denudation during a long period of time would theoretically cause expansion of the rock pores from which the water had previously been expelled by the compaction of the material. In West Virginia, however, the "sands" are, as a matter of fact, competent sandstones; and thus the subject appears to demand further study for that part of the country.

Relation of "drainage area" to production.—As opposed to occasional productivity, the principal function of a syncline or basin in connection with oil accumulation in a petroliferous province of water-saturated sands is to constitute a "drainage area," which has provided the oil for accumulation in porous sands in adjoining upward folds in accordance with the structural theory. Where a great syncline lies opposite a suitable upward fold having the other necessary fundamental conditions, the amount of oil in the structure is likely to be correspondingly large, but the relationship does not hold universally. Hertel shows (Vol. II) that "a large drainage area" is a contributory factor to the amount of oil found at Ventura Avenue, California; Gester and Hawley (Vol. II) make a similar explanation with reference to the Yates pool of Texas; and Hennen (Vol. II) in regard to the Big Lake, McCamey, Church and Fields, Hendricks, and Artesia pools—all "located on the rim of a great structural basin." It is also notable (Vol. II) that the fields of the La Salle anticline in Illinois (Fig. 1) lie opposite the greatest basin in the Illinois geosyncline on the west.

14. INTRA-FORMATIONAL FOLDING

Pertinence of salt domes in this connection.—In addition to the discordances between surface and subsurface strata mentioned under Article 10, there is a fourth type, which calls for a greater degree of speculation. The classic examples of this type are salt domes. Ever since the discovery of the Spindletop field in Texas, controversy has taken place concerning the origin of such structures, and the question is deemed so important that it was made the subject of a former symposium by this Association.[1] Most geologists acknowledge that the salt has flowed to its present plug-like position, but considerable differences of opinion remain as to the

[1] *Geology of Salt Dome Oil Fields* (1926), 787 pp., 230 illustrations.

causes and mechanics of the flowage. However this may be, the salt has taken a position below and between formations of different ages, and in its concentration it has behaved exactly as an incompetent formation would be expected to behave, that is, as mud or putty would have acted if subjected to similar pressures on an experimental scale.

Other intra-formational folding.—But intra-formational folding is not limited to salt and it is not limited to domes. It has occurred in shales in Italy, and it is observable in many anticlines in eastern New Zealand (24), where its resulting surface structures have been considered (probably erroneously) as reflecting the underlying and controlling structures. This type of folding is reported to have taken place extensively in highly contorted and crushed Saman shales of Eocene age on the Jobonillal uplift northeast of Negritos, Peru (46). It has taken place in the Lower Cenozoic of the Topila Hills of Mexico (3) (where the surface folds do not extend down into the underlying Washita formation), and also northeast of Soto la Marina on the eastern flank of the Sierra de Tamaulipas anticline. In the mountainous country west of Panuco, competent limestones 3,000 feet thick have "behaved like wax" and "thousands of feet of Pierre and Fox Hills marls, shales and sandstones, relatively non-competent strata, have been squeezed out of the intervening synclines." Highly crumpled structure that may have a similar cause has been seen by the present writer in the Campanian formation of Palestine, where many thin chert beds, together with their interlaminated shales, have been highly distorted. The effects of a surface zone of this sort are conspicuous at Gemsah, Egypt.

The "flow zones" of Persia and 'Iraq.—Crumpling of the strata like that described seems to have been due to movements that have arisen in certain plastic, semiplastic, relatively plastic, or once plastic strata owing to the compressive effect produced on them by tectonic or other forces acting between underlying and overlying formations having greater competence. British geologists working in the Persian fields have discovered that non-competent beds like salt, gypsum, anhydrite, and certain shales have flowed under pressure to a remarkable degree, whereas the underlying competent limestone and overlying competent sandstones appear not to have been affected. This crumpling of incompetent beds, or "flow zones," as our British confrères call them, is magnificently developed (see diagrams by Richardson [78, 13]) in the Lower Fars series in the Masjid-i-Suleiman and other fields. Some of the most conspicuous surface folds bear no structural relationship to the producing Asmari limestone—a deep-lying competent limestone mainly of Oligocene age.

The pressures which produced the flowage may be due to (*a*) chemical action, (*b*) denudation, or (*c*) tectonic forces; but in any case the pressures have formed a system of anticlines, synclines, and domes near the surface quite diverse from the deep-lying structure of the competent limestone that forms the oil reservoir. Dips in the "flow zone" of the Fars series are as a rule much steeper and far more intricate than are the dips in the underlying, producing limestone, which generally takes the form of a normal anticlinal fold. Here again geophysics has come to the aid of the geologist, and, rather than detracting from the geologist's prestige, has made his work more efficient than ever. It has now become possible for the geologist to decipher structures which previously were indecipherable prior to drilling.

15. RÔLE OF IGNEOUS INTRUSIONS IN OIL-FIELD STRUCTURES

Comparatively little has been written on the existence of igneous intrusions in the anticlines or domes of petroliferous provinces. Intrusions exist near Austin, Texas, and, associated with "serpentine" (igneous or tuffaceous), may be responsible for oil accumulation at Thrall and Lytton Springs (27). That the existence of intrusions is not detrimental to oil occurrence is proved by the many intrusions in the Mexican oil fields; yet geologists in general seem inclined to doubt the existence of any connection between doming and intrusion and between accumulation and intrusion.

Some actual indications of the pertinence of intrusions are known to exist. In the semi-commercial Taranaki field of New Zealand (24) all of the 70,000 or more barrels of oil produced to date have come from a zone surrounding and within a mile of a great andesite intrusion which rises 500 feet above the sedimentary land surface, causing some local geologists to ascribe the origin of Taranaki oil to the distillation effect produced by the igneous mass. In the Panuco field of Mexico igneous rocks are associated with two domes (3), and intrusions exist in or adjoining several Mexican fields. Some geologist has suggested that these intrusions may be of more recent origin than the oil accumulation.

The cause of some doming seems to be laccolitic action, as in the Tow Creek anticline (Vol. II) of northwestern Colorado (Fig. 7), which is cut by a quartz-porphyry intrusion four miles in greatest diameter; yet this anticline constitutes a productive structure. The origin of the Homer and Bellevue, Louisiana, domes is ascribed by Spooner (Vol. II) to igneous intrusions. Theoretically, intrusions might be expected to trap oil in many places. It may be considered surprising that so many similar examples

exist in petroliferous provinces with so little evidence that oil has been trapped by them in quantity; for, up to the present date, the examples of this class of structural occurrence are semi-commercial.

16. RÔLE OF CREVICES AND CAVITIES

Intercommunication of wells due to porosity.—From what has been said in Article 11, it becomes evident that many limestones are creviced. In Mexican and Persian fields the production seems to be greatest at spots of obvious crevicing or solution, evinced by the prompt inter-effect of wells when closed or opened. Comins tells us (28) that, in the Masjid-i-Suleiman field of the second-named country, the rock pressures in localities several miles distant from one another were found to drop "at practically the same rate as in the producing sections" of the field. He acknowledges that the operators are "mostly agreed that the bulk of the fluid contents of the reservoir are contained in crevices, channels, joint planes, fractures and fissures rather than in a truly porous . . . . limestone." The great wells of the "southern" Mexican fields are commonly supposed to owe their phenomenal production to the existence of cavern-like openings, some of which owe their existence to the presence of algal reefs. In the Panuco field production is found along fracture lines and zones. Although the normal intercommunication between different parts of the reservoir in any producing sandstone field had already been proved in the United States (23, 49), the rapidity of intercommunication in the Persian and Mexican limestone fields constitutes evidence of much larger and more numerous openings than are known in sands. The fields of southeastern New Mexico and West Texas[1] produce from porous limestones, some of which represent algal reefs. Egyptian fields also produce from reef limestones.

Shale wells.—Quite different from the (possibly rare) accumulations in obviously great limestone reservoirs are those that become evident from shale wells. A conspicuous example lies on the west side (largely on the outside or on the edge of the closed domal area) in the Salt Creek field, where 59 wells out of a total of 2,160 (excluding the shallow Shannon sand wells) found their production in shale. In Teapot dome a shale well drilled near a fault had a phenomenal initial production.

Examples of small shale production are found in Ohio and Pennsylvania along the south shore of Lake Erie, in eastern Kansas (18), and in

[1] Formations of the Permian basin of the southwestern part of the United States are described in the *Bulletin of the American Association of Petroleum Geologists*, Vol. 13, No. 8 (August, 1929).

the Florence field (Vol. II) of Colorado. Shale oil also exists in fracture zones induced by folding on certain domes of northwestern Colorado (Vol. II). Charles and Page suppose that the Kansas shale gas is held in minute pores, that the size of the wells may be influenced by fracturing and jointing, and that "the amount of fracturing may depend on the intensity of folding or the character of the shale." The Mowry—a hard, brittle, thinly laminated and highly organic shale of Wyoming—is also productive of oil on some structures, especially in the Little Lost Soldier, Wertz, and Ferris fields. Irwin tells us (47) that "no sand members are known to occur in it here, so that it would seem that the oil accumulation is made possible by fissures, faults and pockets induced by the intense deformation along the axes of the sharper folds."

Intensive study of a shale field.—In the present symposium the production of oil from shales has been studied at Florence by De Ford (Vol. II), who approached the problem from the scientific viewpoint in an effort to ascertain why oil has accumulated in that field in the absence of favorable surface structure (which is believed to be fairly representative of the subsurface). The results proved (Plate 1) that (*a*) the structure is homoclinal, with dips ranging from 2° to 5°, though the field is bounded on the east by a steep monocline that brings the productive beds to the surface; and (*b*) the oil occurs in fissures of the Pierre shale. The present writer ventures the suggestion that the Florence occurrence may be a typical synclinal one (perhaps once concentrated through structural causes) where the oil has sunk to the lowest level permitted by the existing water level in the main fissures.

17. CONCLUDING STATEMENTS

Degree of relationship between accumulation and structure.—After a review of the array of evidence presented, it must be admitted that a large proportion of the fields described in the symposium may appear, from a casual viewpoint, to depart from structural principles. Most of the authors prove that the fields reviewed by them bear some relation to structure, but find many examples in which other factors are responsible for the exact position of the oil on a structure.

Unimportance of the so-called "exceptions."—We should not be misled into supposing that the seeming "exceptions" to strict structural occurrence constitute a departure from the principles of the "structural theory" or that they indicate in any manner that oil is not generally related to structure. The "structural theory" does not tell us that oil is limited to anticlines and domes. When the "exceptions" are analyzed a large pro-

portion of them are found to lie in comparatively unimportant fields, in which sand or water conditions or other factors are such that it is a cause for wonder that oil exists at all. Sometimes the "exceptions" are due to non-existence of ideal closure, sometimes to the interruption of the structure by a fault or faults, sometimes to lensing out of the sands, sometimes to absence of folds but presence of inclined sand lenses, sometimes to unconformable relationships, and sometimes to the absence of water in the sands.

Universality of structural principles.—But, in connection with all the "exceptions," the observer can hardly fail to note that the principles of structural relationship (the differences in specific gravities between oil, water, and gas—qualified by the essential question of the presence or absence of water in the particular sand under consideration) are ever operative. In all fields that contain water-saturated sands, oil has its paramount tendency to ascend into the highest accessible point in any sand. In fields in which the sands are water-free, the oil tends to descend to the lowest point at which a sand is sufficiently porous in any syncline. Since by far most of the known fields are in regions of water saturation, the geologist seems to be justified in assuming that the sands are saturated unless information to the contrary exists; yet he must be constantly on the watch for indications that the region may be one of water-free sands.

Importance of fundamental conditions.—Furthermore, we all know of fields which would never have been discovered on the basis of structural evidence alone. Much time and money have been expended in a search for oil in certain regions in which structural conditions were supposedly obvious, when this effort applied in regions of more favorable fundamental conditions but less obvious surface structure might have resulted successfully. It should be recognized that, in order that oil may exist anywhere, first of all there is need for suitable fundamental conditions. The most adequate structural relationships will avail nothing if the conditions enumerated in Article 2 be unsuitable.

Justification for structural search.—The geologist seems justified in continuing to search for favorable structure (surface or subsurface) in any fundamentally favorable geologic province, as well as in searching for the crest of any structure that is considered to have the essentially fundamental conditions for possible production; yet, if the first test wells result in disclosing unsatisfactory porosity, unconformable or hydrostatic conditions, he should not admit failure until after exhaustively appraising the situation to determine whether some other part of the structure or of adjoining structure may have more favorable conditions.

Rôle of geophysics.—Let nobody suppose that geology has sacrificed prestige because it has called in geophysics to solve certain problems. We have simply progressed to a stage in advance of the period at which surface or obvious structures alone were looked for. The complexities of earth structure are being revealed as more surprising every year; and we find that illusive salt domes, "buried hills," and anticlines concealed beneath "flow zones," which are not evident from the surface, can be discovered by supplementing our visual observations with geophysical researches. Our science is none the less "geological" than it was before; the interpretation and final verdict of the geologist are no less essential than ever; but, through our geophysical methods, we are reaching out into the unknown. Perhaps the future may hold something even more wonderful in store for its investigators; but, in any case, we must not abandon our faith in structure. Every seeming "exception" clinches the structural principles more strongly than before, and we can advance with a greater degree of understanding of our difficulties and a keener appreciation of the pitfalls and the means for avoiding them.

Conclusion.—If some supposed "exception" to the operation of structural principles seems to have been given inadequate treatment in this symposium, in the writer's review of it or elsewhere in the literature, let us do our best to fathom the facts and to ascertain in what way the operation of structural principles has been controlled by other factors. In every case the answer will doubtless be found not to be an infraction of the principles or an obstacle to oil development, but a lesson that will assist in the discovery or development of fields elsewhere.

In any geological discussion of American oil fields it may be important to bear in mind the fact that the United States, though it produces at the present time 68.2 per cent of the world's annual output of crude oil (72), has been estimated to contain only 18 per cent of the world's oil reserves (90), and that the lessons learned in our own country must be applied sooner or later to the development of new foreign fields, which may exist in many countries in which oil has not yet been discovered to exist commercially.

18. LIST OF REFERENCES CITED

1. Robert Anderson and R. W. Pack, "Geology and Oil Resources of the West Border of the San Joaquin Valley North of Coalinga, California," *U. S. Geol. Survey Bull. 603* (1915).
2. E. B. Andrews, *Amer. Jour. Sci.*, 2d ser., Vol. 32 (1861), pp. 85–93.
3. C. L. Baker, "Panuco Oil Field, Mexico," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 395–441.

4. J. G. Bartram and Louis Roark, "The Healdton Field, Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 5 (1921), pp. 469–74.
5. J. S. Barwick, "The Salina Basin of North-Central Kansas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 177–99, 5 figs.
6. C. Max Bauer, "Oil and Gas Fields of the Texas Panhandle," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 733–46; "Gas a Big Factor in the Texas Panhandle," *ibid.*, Vol. 12 (1928), pp. 165–76.
7. C. H. Beal, "The Decline and Ultimate Production of Oil Wells, with Notes on the Valuation of Oil Properties," *U. S. Bur. of Mines Bull. 177* (1919), 215 pp., 4 pls., 80 figs.
8. C. H. Beal and J. O. Lewis, "Some Principles Governing the Production of Oil Wells," *U. S. Bur. of Mines Bull. 194* (1921). 58 pp., 2 pls., 8 figs.
9. Eliot Blackwelder, "Origin of the Central Kansas Oil Domes," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 4 (1920), pp. 89–94.
10. C. A. Bonine, "Anticlines in the Clinton Sand near Wooster, Wayne County, Ohio," *U. S. Geol. Survey Bull. 621-h* (1916), pp. 87–98, 1 pl.
11. Josiah Bridge and C. L. Dake, "Initial Dips Peripheral to Resurrected Hills," *Missouri Bur. of Geol. and Mines 55th Biennial Rept.* (1929), Appendix I. 7 pp., 1 pl.
12. R. W. Brown, "Origin of the Folds of Osage County, Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 501–13.
13. H. G. Busk, *Earth Flexures* (Cambridge, England: The Oxford Press, 1929).
14. H. G. Busk and H. T. Mayo, "Some Notes on the Geology of the Persian Oilfields," *Jour. Inst. Petrol. Tech.*, Vol. 5 (1918), pp. 3–33.
15. Charles Butts, "Oil in Lee County, Virginia," *U. S. Geol Survey Press Notice* (July 3, 1923).
16. W. K. Cadman, "The Golden Lanes of Greenwood County, Kansas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 1151–72, 10 figs. 1 pl.
17. M. R. Campbell and Others, "The Valley Coal Fields of Virginia," *Virginia Geol. Survey Bull. 25* (1925), pp. 76–90.
18. H. H. Charles and J. H. Page, "Shale-Gas Industry of Eastern Kansas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 367–81, 4 figs.
19. F. G. Clapp, "The Use of Geological Science in the Petroleum and Natural Gas Business," *Proc. Eng. Soc. W. Pennsylvania*, Vol. 26 (1910), pp. 87–120.
20. ———, "Notes on the Occurrence of Oil and Gas Accumulations in Formations Having Monoclinal Dips," *Econ. Geol.*, Vol. 6 (1911), pp. 10 ff.
21. ———, "The Occurrence of Oil and Gas Deposits Associated with Quaquaversal Structure," *Econ. Geol.*, Vol. 7 (1912), pp. 364–81.
22. ———, "Revision of the Structural Classification of Petroleum and Natural Gas Fields," *Bull. Geol. Soc. Amer.*, Vol. 28 (1917), pp. 553–602, 20 figs.
23. ———, "Report on Teapot Dome, Naval Reserve No. 3, Wyoming, in Hearing Before the Committee on Public Lands and Surveys," *U. S. Senate Doc. 191*, 67th Cong., 2d Sess. (1923), pp. 111–54.

24. ———, "Oil and Gas Prospects of New Zealand," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 1227–60, 1 fig.
25. ———, "Fundamental Criteria for Oil Occurrence," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 683–703.
26. B. L. Clark, "Tectonics of the Valle Grande of California," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 199–238.
27. D. M. Collingwood and R. E. Rettger, "The Lytton Springs Oil Field, Caldwell County, Texas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 953–75.
28. D. Comins, "Unit Operation of Oil Fields," *Bull. Amer. Petrol. Inst.*, Vol. 10, No. 2 (January 3, 1929), pp. 32–36.
29. F. C. Edson, "Ordovician Correlations in Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 967–75.
30. E. L. Estabrook, "Faulting in Wyoming Oil Fields," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), p. 95.
31. E. W. Evans, *Amer. Jour. Sci.*, 2d ser., Vol. 32 (1866), pp. 334–43.
32. A. E. Fath, "The Origin of the Faults, Anticlines and Buried 'Granite Ridge' of the Northern Part of the Mid-Continent Oil and Gas Field," *U. S. Geol. Survey Prof. Paper 128-c* (1921), pp. 75–84, 3 pls.
33. L. S. Fox, "Structural Features of the East Side of the San Joaquin Valley, California," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 101–8.
34. M. Gignoux and C. R. Hoffmann, "Le Bassin Pétrolifère de Péchelbronn," *Service de la Carte Gélogique d'Alsace et de Lorraine* (Strasbourg, 1920).
35. C. N. Gould and Others, "Oil and Gas in Oklahoma," *Oklahoma Geol. Survey Bull. 40* (1926–29), by counties.
36. W. T. Griswold and M. J. Munn, "Geology of Oil and Gas Fields in Steubenville, Burgettstown and Claysville Quadrangles, Ohio, West Virginia, and Pennsylvania," *U. S. Geol. Survey Bull. 318* (1907). 196 pp., 13 pls.
37. Burton Hartley, "Certain Relations Between Production and Structure in Northern Osage County, Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 6 (1922), pp. 464–71.
38. A. D. Hedberg, "The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 1035–72.
39. A. B. Hendrickson, "Report on the Kern Front Area of the Kern River Oil Field," *California State Min. Bur. Summary of Operations California Oil Fields*, Vol. 13, No. 7 (1928).
40. D. F. Hewitt and C. T. Lupton, "Anticlines in the Southern Part of the Big Horn Basin, Wyoming," *U. S. Geol. Survey Bull. 656* (1917).
41. F. F. Hintze, "Oil Accumulations in Relation to Periods of Folding," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), pp. 58–66.

42. O. B. Hopkins and Sidney Powers, "T. 24 N., Rs. 11 and 12 E.," *U. S. Geol. Survey Bull. 686-s* (1922), pp. 237–53, 4 pls.
43. W. V. Howard, "A Classification of Limestone Reservoirs," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 1153–61.
44. E. Huguenin, "The Minor Oil Fields of Kern County," *California State Min. Bur. Summary of California Oil Fields*, Vol. 9, No. 12 (1924).
45. T. Sterry Hunt, "Notes on the History of Petroleum or Rock Oil," *Can. Nat.*, Vol. 6 (1861), pp. 241–55; *Canada Geol. Survey 17th Rept. of Progress* (1863–66), p. 233.
46. Arthur Iddings and A. A. Olsson, "Geology of Northwest Peru," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 1–39, 3 figs.
47. J. S. Irwin, "Faulting in the Rocky Mountain Region," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), p. 105.
48. Walter Kauenhowen, "Oil Fields of Germany," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 463–99, 8 figs.
49. J. O. Lewis, "Report of the Geological Conditions of Teapot Dome (Naval Reserve No. 3, Wyoming), in Hearing Before the Committee on Public Lands and Surveys," *U. S. Senate Doc. 191*, 67th Cong., 2d Sess. (1923), pp. 69–110.
50. T. A. Link, "*En Échelon* Tension Fissures and Faults," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 627–43.
51. E. R. Lloyd, "Capitan Limestone and Associated Formations of Texas and New Mexico," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 645–58.
52. G. C. Matson, "Gas Prospects South and Southeast of Dallas," *U. S. Geol. Survey Bull. 629* (1916).
53. W. J. Mead, "Notes on the Mechanics of Geological Structure," *Jour. Geol.*, Vol. 28 (1920), pp. 505–23.
54. A. F. Melcher, "Texture of Oil Sands with Relation to the Production of Oil," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 8 (1924), pp. 716–74.
55. H. C. Miller, "Function of Natural Gas in the Production of Oil," printed by *Amer. Petrol. Inst.* (1929), 267 pp., 36 figs., 29 tables.
56. R. Van A. Mills, "Natural Gas as a Factor in Oil Migration and Accumulation in the Vicinity of Faults," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), pp. 14–24.
57. H. D. Miser, "Geologic Structure of San Juan Canyon and Adjacent Country, Utah," *U. S. Geol. Survey Bull. 751* (1925).
58. A. N. Murray, "Limestone Reservoirs of the Northeastern United States and Ontario, Canada: I, The Relations of the Producing Horizons to Unconformities," manuscript submitted to *Amer. Petrol. Inst.*
59. C. M. Nevin and R. E. Sherrill, "Studies in Differential Compaction," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 1–22, 10 figs.
60. ———, "The Nature of Uplifts in North-Central Oklahoma and Their

Local Expression," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 23–30.
61. C.-P. Nicolesco, "Gisements Pétrolifères de la Perse," published by *La Revue Pêtrolifère* (Paris, 1928), 79 pp., 40 figs.
62. K. B. Nowels, "Oil Production in Rattlesnake Field," *Oil and Gas. Jour.* (June 7, 1928), pp. 106–7, 143–44.
63. Edward Orton, *Science*, Vol. 7, p. 563.
64. ———, *Geology of Ohio*, Vol. 6 (1888), p. 94.
65. R. W. Pack, "The Sunset-Midway Oil Field, California," *U. S. Geol. Survey Prof. Paper 116* (1920), p. 75.
66. Sidney Powers, "The Healdton Oil Field, Oklahoma," *Econ. Geol.*, Vol. 12 (1917), pp. 594–606; "Age of the Oil in Southern Oklahoma Fields," *Trans. Amer. Inst. Min. Eng.*, Vol. 59 (1918), pp. 564–75.
67. ———, "Reflected Buried Hills and Their Importance in Petroleum Geology," *Econ. Geol.*, Vol. 17 (1922), pp. 233–59.
68. ———, "Crinerville Oil Field, Carter County, Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 1067–85, 6 figs.
69. ———, "The Seminole Uplift, Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 1097–1108, 4 figs.
70. ———, "Buried Ridges in West Texas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 1109–15, 2 figs.
71. ———, "Structural Geology of the Mid-Continent region: A Field for Research," *Bull. Geol. Soc. Amer.*, Vol. 36 (1925), 379–92.
72. A. H. Redfield, "Petroleum Resources of Foreign Countries and Outlying Possessions of the United States," Appendix C of *Report III of the Federal Oil Conservation Board to the President of the United States* (February 25, 1929), pp. 50–191.
73. R. D. Reed, "Some Suggestions in Regard to Pennsylvanian Paleogeography in the Henryetta District, Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), pp. 50–57.
74. B. C. Renick, "Recently Discovered Salt Domes in East Texas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 527–47, 1 pl.
75. John L. Rich, "Shoestring Sands of Eastern Kansas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), pp. 103–13.
76. ———, "Further Observations on Shoestring Oil Pools of Eastern Kansas," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 568–80.
77. ———, "Buried Pennsylvanian Channels and Sand Bars of Eastern Kansas" (Abstract), *Bull. Geol. Soc. Amer.*, Vol. 37, No. 1 (March, 1926), p. 159.
78. R. K. Richardson, "The Geology and Oil Measures of South-West Persia," *Jour. Inst. Petrol. Tech.*, Vol. 10 (1924), pp. 256–96, 17 pls.
79. R. E. Sherrill, "Origin of the *En Échelon* Faults in North-Central Oklahoma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 31–37.

80. L. D. Stamp, "The Geology of the Oil Fields of Burma," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 557–75.
81. K. Tolwinski, "Les Carpates Bordières de Skole, Géologie de Boryslaw y Comprise," *Service Géologique de Pologne Bull. 8* (Boryslaw, 1925); also "*Carte Structurale*," *Bull. 19* (1929).
82. W. T. Thom, Jr., "Synclinal Oil Occurrences and Regional Uplift," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 554–55.
83. A. Beeby Thompson, *Trans. Inst. Min. and Met.*, Vol. 20 (1910–11), p. 229.
84. S. A. Thompson and O. H. Eichelberger, "Vinton Salt Dome, Calcasieu Parish, Louisiana," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 12 (1928), pp. 385–95, 2 figs., 1 pl.
85. W. A. J. M. van Waterschoot van der Gracht, "The Structure of Salt Domes of Northwest Europe as Revealed in Salt Mines," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 9 (1925), pp. 326–30.
86. C. W. Washburne, "The Florence, Colorado, Oil Field," *U. S. Geol. Survey Bull. 381-d* (1910), pp. 517–44, 1 pl.
87. ———, "Epi-Anticlinal Faults of Elk Basin, Wyoming," *Bull. Geol. Soc. Amer.*, Vol. 39 (1927).
88. Theron Wasson and J. H. Sinclair, "Geological Explorations East of the Andes in Ecuador," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 1253–78, 4 figs., 4 pls.
89. C. H. Wegemann, "The Salt Creek Field, Wyoming," *U. S. Geol. Survey Bull. 670* (1918), 52 pp., 2 figs., 7 pls.
90. Roy W. West and Others, "Existing Petroleum Situation in the United States," in *Report III of the Federal Oil Conservation Board to the President of the United States* (February 25, 1929), pp. 1–8.
91. David White and Others, "Structure and Oil and Gas Resources of the Osage Reservation, Oklahoma," *U. S. Geol. Survey Bull. 686* (1922), 427 pp., 60 pls.
92. I. C. White, *Science*, Vol. 6 (June 26, 1885); *Bull. Geol. Soc. Amer.*, Vol. 3 (1892), pp. 187–216; *West Virginia Geol. Survey*, I-A (1904), pp. 48–64.
93. ———, *Bull. Geol. Soc. Amer.*, Vol. 10 (1899), p. 29.
94. R. B. Whitehead and R. H. Fash, "A Study of the Application of Oil Field Water Analyses to the Fault Zone Type of Accumulation," read before Amer. Assoc. Petrol. Geol. at Houston, Texas (1924).
95. V. H. Wilhelm and L. W. Saunders, "Report on the Mt. Poso Oil Field," *California State Min. Bur. Summary of Operations California Oil Fields*, Vol. 12, No. 7 (1927).
96. Neil Williams, "Many Salt Domes Discovered in 1928," *Oil and Gas Jour.* (January 31, 1929), pp. 156, 159, 260, and 262.
97. A. Windhausen, "Lineas Generales de la Constitucion Geologica de la Region al Oeste del Golfo de San Jorge," *Bulletin del Academia de Ciencia en Cordoba*, Vol. 27 (1924), Pl. 9.

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